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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Advanced Control Systems for Aircraft Powerplants

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The Propulsion and Energetics Panel wishes to express its thanks to the German National Delegates to AGARD for the invitation to hold its 54th Meeting in Cologne, and for the personnel and facilities made available for this meeting.

CONTENTS

SPACE SHUTTLE MAIN ENGINE

DIGITAL CONTROLLER

by

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SUMMARY

The controller, which is an electronic package mounted on the SSME, operates in conjunction with engine sensors, valves, actuators, and spark igniters to provide a self-contained system for engine control, checkout, and monitoring.

The controller provides responsive control of engine thrust and mixture ratio through the digital computer in the controller, updating the instructions to the engine control elements 50 times per second (every 20 milliseconds). Additionally, precise engine performance is achieved through closed-loop control, utilizing 16-bit computation, 10-bit input/output resolution, and self calibrating analog-to-digital conversion. Engine reliability is enhanced by a dual redundant control system that allows normal operation after the first failure and a fail-safe shutdown after a second failure.

The digital computer is programmable, allowing modification of engine control equations and constants by change of the stored program (software).

The controller is packaged in a sealed, pressurized chassis with cooling provided by convection heat transfer through pin fins as part of the main chassis. The electronics are distributed on functional modules having special provisions for thermal and vibrational protection.

PREFACE

The Space Shuttle Main Engine is a reusable, high performance, Liquid Hydrogen/Oxygen, rocket engine, designed and produced by the Rocketdyne Division of Rockwell International under contract with the Marshall Space Flight Center. Three of these engines are utilized per Space Shuttle and are mounted in a clustered configuration on the aft end of the orbiter. The engines are started and reach 90% thrust before the two Solid Rocket Boosters are ignited and vehicle lift-off occurs. After approximately 2-1/2 minutes, the Solid Rocket Boosters burn out, are jettisoned, and the SSME is the sole source of thrust for an additional six minutes until the vehicle almost achieves orbital altitude and velocity. At this point, the SSME's are shutdown and the large propellant tank (External Tank) is jettisoned from the orbital vehicle. The three SSME's then dump the residual propellant left in the orbiter feed lines. Subsequent to the propellant dump, the SSME's are turned off and are no longer used during that orbital flight or re-entry. In order to meet mission acceleration requirements, the engine thrust is variable in 1% increments, as commanded by the orbiter, from 65% to 109% of rated thrust 470,000 pounds (2,090,660 Newtons). The engine burn time is a mission dependent variable. Nominal burn time is approximately 8.5 minutes, but could be extended to as long as 13.7 minutes in the event of certain abort profiles.

Basically, the engine system is composed of two liquid oxygen turbopumps (low pressure and high pressure), two liquid hydrogen turbopumps (low pressure and high pressure) main combustion chamber, nozzle and a control system (Figure 1).

Each of the two high pressure turbopumps is powered by a separate preburner. The staged-combustion cycle burns low mixture ratio propellants in the preburner first. The resulting hydrogen rich gases in turn drive the high pressure turbopumps and are then routed to the main combustion chamber where the remaining oxygen is provided and the final thrust producing combustion is achieved.

Thrust control is achieved by adjusting the power available to the high pressure oxidizer pump. This is accomplished by modulation of the oxidizer preburner oxidizer valve. Similarly, mixture ratio of 6.0 (O/F) is maintained by modulation of the fuel preburner oxidizer valve which adjusts the power available to the high pressure fuel pump. In addition to these two preburner valves three other propellant valves (main fuel, main oxidizer, and chamber coolant) are position scheduled as a function of thrust level to provide proper propellant flow during engine start, mainstage, and shutdown operations.

SSME PROPELLANT FLOW SCHEMATIC

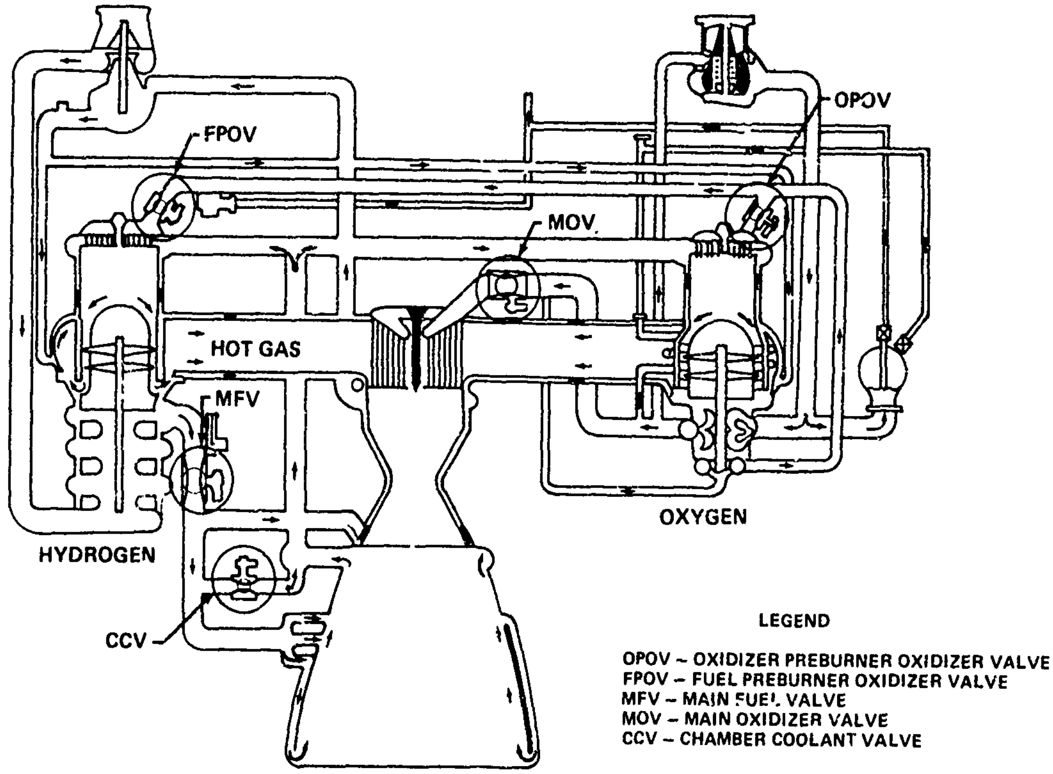

FIGURE 1

CONTROL SYSTEM

A fast response control system is necessary in order to accomplish throttle control and to maintain engine mixture ratio balance over the entire throttle range. Additional requirements for the control system include providing repeatable start and shutdown operations, capability to monitor engine operating condition, and manage engine component redundancy during flight. This control system, utilizing special software modules, also performs self contained engine pre-launch checkout. The control system is implemented as a fully programmable digital system. This provides the flexibility and ease of change needed during engine R&D phases as well as the autonomy and adaptability required when fully operational. The programmable digital computer and associated interface electronics is called the controller. The controller receives data for real time processing from sensors (temperature, pressure, speed, flow, position) spark igniters, and five hydraulically actuated and electronically managed propellant valves. The combination of a digital computer, data generating devices, and responding propellant valve actuators, and solenoids for open/close functions make up the control system for the SSME. The control system has full authority over the operation/performance management of the engine. All logic necessary for the control system to meet its requirements is contained in the flight operational software program. In order to obtain the necessary fast response, a major cycle processing time of 20 milliseconds is established. Thus, all engine control, monitor and redundancy management functions are accomplished 50 times per second.

Since a digital computer is used on the engine, the interface and interaction between the orbiter vehicle and the engine is a command/response and data providing activity. For example, to achieve an engine start, the orbiter need only give the engine a single command - "start". The controller acknowledges receipt of the command and then accomplishes the complex task of igniting the engine and controlling it up to 100% thrust within the required 3.9 seconds, all without further involvement from the orbiter.

There are two distinct engine operating modes that are regulated and monitored by the controller and its software. There is a ground checkout mode and a flight operational mode. The software is structured such that basic executive, control, and monitor logic is resident at all times and individual separately loaded overlay modules are used for the various engine tests performed during the ground checkout mode. A single flight module overlay is required for the flight operational mode.

GROUND CHECKOUT MODE

Ground checkout of the engine is accomplished through 6 separate software modules. Each checkout module is self-contained and is designed to perform an automatic checkout of an engine functional subsystem. Each checkout module, once loaded and initiated, automatically proceeds either to a successful conclusion, or if unsuccessful, data is provided to the ground which isolates the fault to a line replaceable unit. Functional subsystems checked automatically include, the controller, sensors, propellant valve actuators, pneumatic solenoid and check valve, spark ignitor, and all inter-connecting electrical harnesses.

In addition to the specialized checkout modules a Flight Readiness Test module (FRT) is also provided. This module allows simulation of the engine's flight mode. All operational flight commands are accepted and the engine performance is simulated such that a high fidelity orbiter/vehicle mission simulation can be performed.

OPERATIONAL MODE

The flight operational mode consists of 5 phases, start preparation, start, mainstage, shutdown, and post shutdown.

Start Preparation Phase - The engine system is conditioned for start during this phase. Upon orbiter command, the controller sequences, regulates, monitors the fuel and oxidizer system purges which inert and dry the engine prior to admitting propellants. Propellants are then admitted to the engine and are recirculated to ensure proper engine thermal conditioning prior to start. The controller monitors the engine operational readiness and provides an "engine ready" signal to the orbiter when all conditions are acceptable for an engine start. The "engine ready" includes requirements such as fuel and oxidizer temperatures and pressures are within acceptable ranges, hydraulic and pneumatic pressure within limits, controller self-test satisfactory, propellant and pneumatic valves in start position, etc..

Start Phase - The controller will accept a start command from the orbiter only if the "engine ready" conditions are satisfied at the time of command receipt. The start sequence is composed of, first, an open-loop and then a closed-loop control mode. During the open-loop mode the spark igniters in each of the three combustion chambers are energized and the propellant valves are time sequenced in order to achieve ignition in the proper sequence of the fuel and oxidizer preburners and the main combustion chamber. Closed-loop control is initiated at 0.6 seconds in the start. Initial power buildup of approximately 20% rated thrust is accomplished within 2.35 seconds. During this time period, the controller monitors selected engine performance parameters to ensure proper ignition, acceleration of the high pressure turbopumps, and thrust buildup. Should these parameters not achieve specified values, the controller will automatically shut the engine down. When the final ignition confirmation of 20% thrust level is successfully accomplished at 2.35 seconds, the controller regulates power buildup such that 100% thrust level is achieved by approximately 3.9 seconds.

Mainstage Phase - The engine performance is regulated by two inter-related closed-loop control systems; one for thrust and the other mixture ratio (Figure 2). Engine operating thrust is sensed by measuring the main combustion chamber pressure. The value is compared against the orbiter commanded thrust and the resultant error signal is used to determine a position command for the oxidizer preburner oxidizer valve. These computations are performed 50 times per second (every 20 milliseconds) and the valve position adjusted as needed to maintain thrust performance within specified limits. The controller will accept commands to adjust engine thrust from the orbiter in 1% increments from 65% to 109% rated thrust with a maximum thrust rate of change of 10% per second.

Engine mixture ratio is maintained in a similar manner at a constant 6.0. The mixture ratio is computed (50 times per second) from measurements of fuel flow, propellant temperature and pressure, and main combustion chamber pressure. The computer mixture ratio is compared to the required 6.0. The error signal, compensated by current thrust level, is used to position the fuel preburner oxidizer valve. An important aspect provided by the closed-loop feedback control system is that control precision is not affected by shifts in engine component operating characteristics such as caused by wear or thermal effects. Control precision depends only on sensor calibration and main combustion chamber calibration. Each sensor is individually calibrated and the calibration data is stored in the controller software; therefore, all measured data is properly calibration compensated prior to use in the control equations. Main combustion chamber calibration is obtained during engine acceptance test firings and this data is also used in solution of the control equation. Once the engine is calibrated, the calibration is maintained by the closed-loop control system. Sensor replacements can be accommodated without requiring an engine recalibration firing by updating the software with the calibration constants for the new sensor.

Shutdown Phase - Shutdown may be entered from any engine operating point including, as previously discussed, start. In normal mission operation the orbiter will throttle the engine to 65% thrust for approximately 10 seconds and then command shutdown just prior to orbit insertion. The shutdown sequence is an open-loop mode and consists of time dependent position schedules for the five propellant valves. The valve schedules are modified as a function of actual position at time of shutdown initiation so that thrust decay rates and engine operating temperatures are maintained with allowable limits. During the final portion of shutdown, selected purging is accomplished. Purge initiation timing is dependent on engine power level at shutdown.

The controller also has software and hardware logic to select a special pneumatically driven shutdown sequence in the event certain failures occur which prevent hydraulic position control of the propellant valves. This shutdown mode is achieved by the controller deactivating the hydraulic actuators servovalve controls and a pneumatic control solenoid. This establishes a pneumatic circuit which performs a sequenced closing of the propellant valves.

SSME CONTROL LOOPS

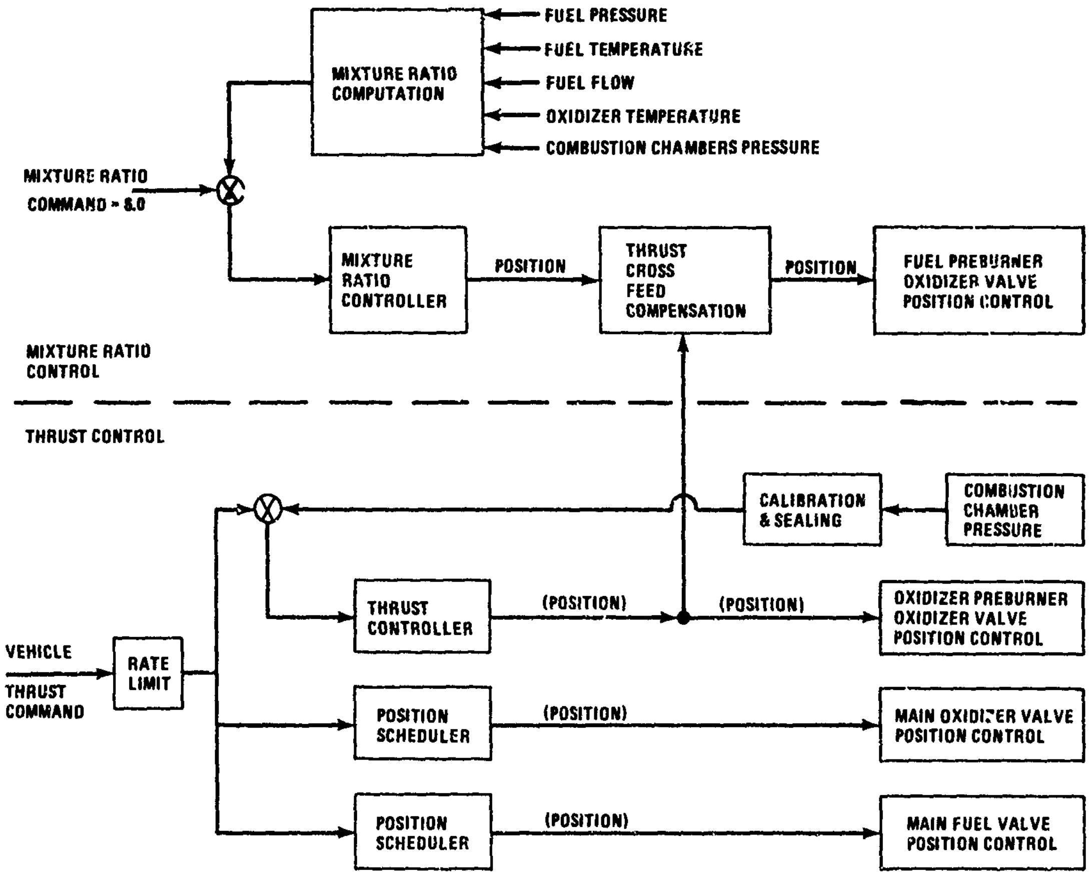

FIGURE 2

Post-Shutdown Phase - After engine shutdown the orbiter separates from the "External Tank". Propellant residuals trapped in the feed lines in the orbiter are then separately exhausted through the engines. The engine's sequencing and pruging to perform this propellant dump is regulated and monitored by the controller upon command from the orbiter.

ENGINE LIMIT MONITORING AND REDUNDANCY MANAGEMENT

In order to protect the orbiter from a catastrophic engine malfunction selected engine parameters are monitored by the controller. Redline limits are set into the software and compared against actual measured values 50 times a second. Should the redline criteria for a parameter be met, the controller will, if enabled by the orbiter, shut the engine down. The redline criteria for a parameter includes not only a maximum allowable value but also the number of consecutive readings (20 milliseconds apart) the parameter must exceed the maximum allowable value. The number of consecutive readings set in the software is normally three; thus, a parameter must "strike" above redline values three consecutive times (3strikes) before an engine shutdown is initiated. This "strike" criteria implemented into the software helps ensure that the condition observed is truly a malfunction and not the result of a temporary operating anomaly or momentary data error. As previously stated, exceedance of an engine redline will result in an engine shutdown only if enabled by the orbiter. Since the engines operate totally independent of each other, the decision to enable or inhibit shutdown is vested in the orbiter as it may be necessary, for vehicle and crew safety reasons, to continue operation of an engine above redline limit.

The control system is a dual redundant hardware mechanization in order to provide fail operational/ fail safe capability. A large part of the flight operational software is devoted to failure detection and management of the dual redundant hardware. The details of this redundancy and its management will be discussed later.

One aspect of the redundancy management is to provide for a degraded or "lock-up" mode of engine operation in the event of concurrent failure of a performance control parameter.

For example, an electronic lock-up mode is entered in event of total loss of the main combustion chamber pressure parameter. The thrust and mixture ratio controls loops can no longer be implemented since they depend on the measured value of the main combustion chamber pressure. The controller notifies the orbiter and enters a lock-up mode in which it will no longer accept thrust change commands, deactivates the thrust and mixture ratio control loops and maintains the propellant values at their last command position. This allows the engine to continue to produce thrust although its performance may degrade.

The engine will continue to operate in this mode for the remainder of the mission or until a redline condition is detected by the controller. The other "lock-up" mode (hydraulic lock-up) will be entered when the controller determined that both electronic servo control channels of a hydraulic actuator have failed. The controller would deactivate the actuator which allows hydraulic pressure to equalize on both sides of the actuator. This causes the actuator to hydraulically lock the propellant valve at its current position. The engine will continue to operate in this mode until the system drifts and a redline is exceeded or a shutdown is commanded. The shutdown will be accomplished by the previously discussed pneumatic mode since hydraulic control can no longer be effected.

HARDWARE MECHANIZATION

All critical electrical hardware components are redundant in order to provide fail operational/ fail safe capability. A basic design requirement is that there shall be no electrical single-point failure which will result in loss of controller function, engine shutdown, or an unsafe operating condition. The system is shown schematically in Figure 3. The mechanization is such that all elements, either sensing or control, which are utilized in engine readiness determination, performance control or limit monitoring are dual redundant.

CONTROL SYSTEM ORGANIZATION

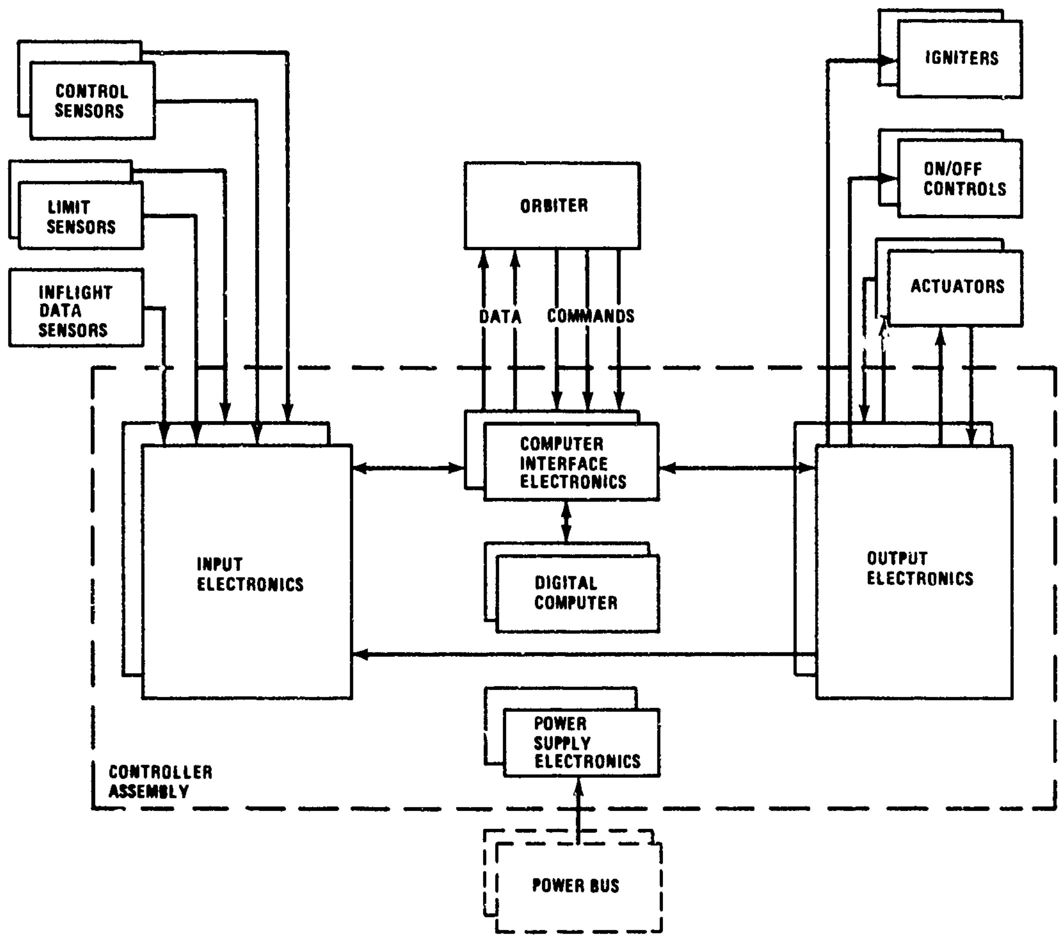

FIGURE 3

The controller, which is designed and manufactured by Honeywell, Incorporated, is an integral electronics package and is mounted directly on the engine thrust chamber. The engine subjects the controller to a very hostile vibro-acoustic and thermal environment. Air temperature surrounding the controller will vary, depending on engine operating phase, from +95 degrees F to -55 degrees F, while atmospheric pressure varies from ground ambient to the near vacuum of space. An acoustic impingment of 160 db is encountered just after vehicle lift-off. The vibration environment as depicted in Figure 4 is presented throughout the engine burn time. The controller is required to operate within this environment for 55 missions.

In order to minimize vibration input, the controller is mounted to the engine at four points through elastomeric vibration isolators. These isolators greatly reduce the vibration input to the controller as can be seen in the dashed curve of Figure 4.

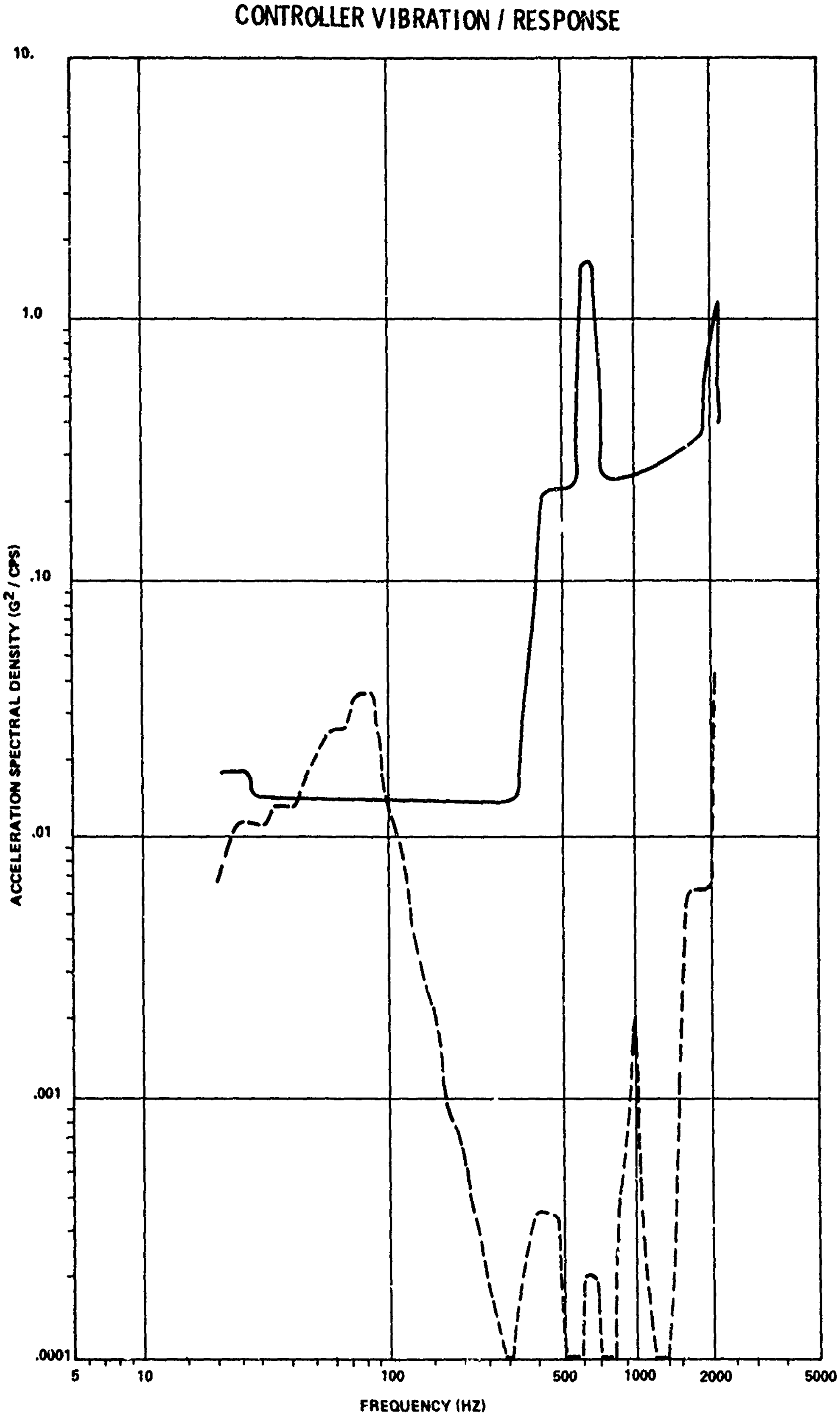

FIGURE 4

The controller electronics are mounted on conventional printed circuit cards. The printed circuit cards are retained in the controller chassis by a rigid foam packaging system which further isolates the electronics from the vibro-acoustic environment. In this packaging system (Figure 5), the chassis is divided into cavities each of which accepts two cards. Each card has an open foam grid attached to the component mounting side and a foam half wedge attached to the back side. The cards are retained in the chassis cavity by loading a foam wedge between the two cards. This provides for very tight card retention as well as isolation from vibration transmitted through the chassis and detunes the printed circuit card/chassis structure system. The foam grids, which are in contact with both the printed circuit cards

and the chassis walls, have an aluminum foil surface which provides heat transfer from the electronics parts. Cooling is accomplished by convective heat transfer through the chassis. Additional surface area is obtained by extensive use of pin fins machined into the chassis. The controller chassis is hermetically sealed and pressurized.

PRINTED CIRCUIT BOARD RETENTION DESIGN

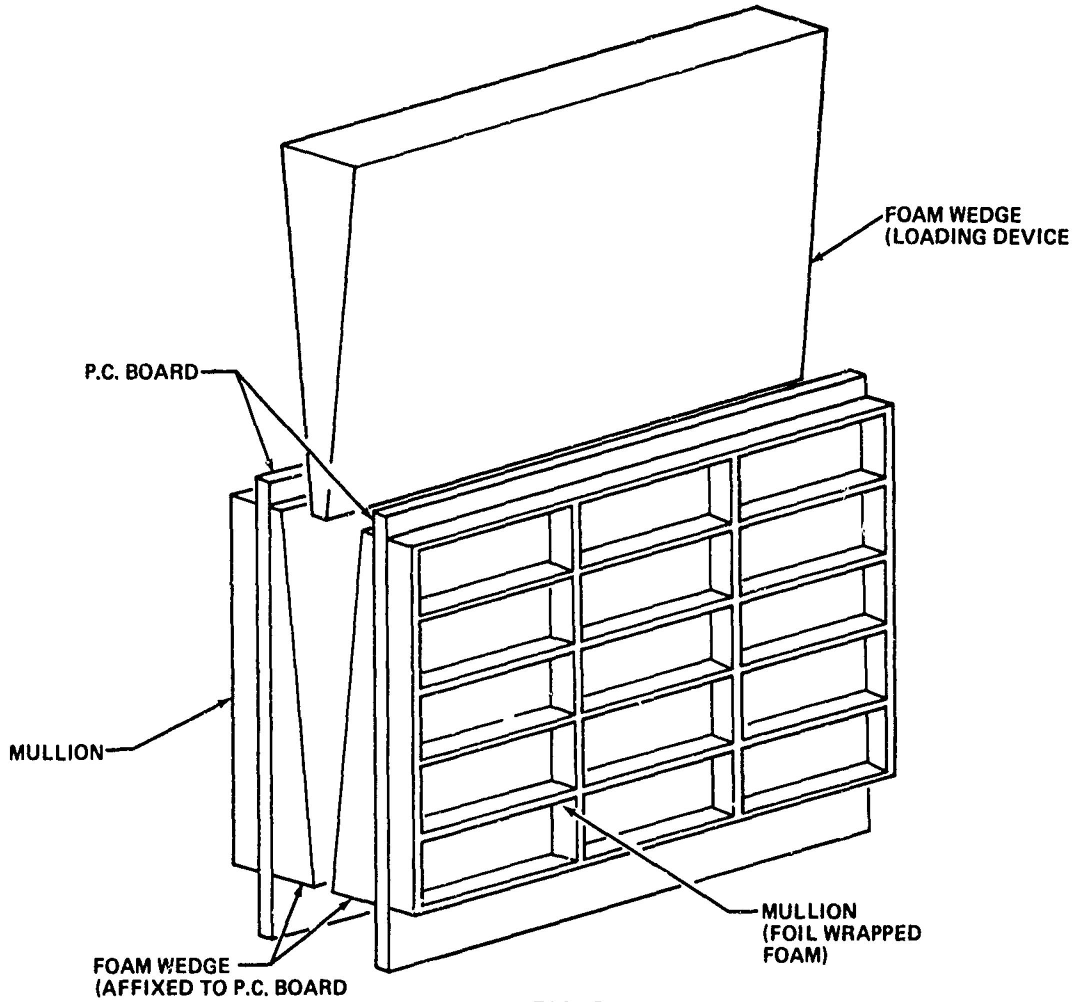

FIGURE 5

A functional block diagram of the controller is shown in Figure 6. The controller is dual redundant with internal cross-strapping to maximize the probability of successfully completing a mission in the event of an internal failure. It consists of five major subassemblies each of which are dual redundant.

Digital Computer - The Digital Computer has a memory capacity of 16,384 words, is fully programmable, and has a memory cycle time of 1_{us}. The memory storage element is 2 mil plated wire. Each word is 17-bits long including a parity bit. Even parity is required for each memory read.

The central processor provides a full set of algebraic, logical and input/output control instructions. The addressing scheme allows both direct and multi-level indirect address modification.

Computer Interface Electronics - The Computer Interface Electronics (CIE) interfaces the computer to the input and output electronics, and provides the command and data interface with the orbiter. It mechanizes a Direct Memory Access capability which operates on a memory cycle steal basis and completely refreshes all input data in computer memory every 20 milliseconds with minimum software intervention.

Input Electronics - All interface between the controller and the engine sensors is provided by the input electronics. Temperature and pressure measurements are accomplished through resistor bridge circuits. There is a separate bridge circuit for each temperature and pressure sensor all of which are multiplexed and read by a single 10-bit analog-to-digital converter. Pump speed and fluid flow transducers generate a pulse train of which the frequency is velocity dependent. The controller reads these measurements by determining time between consecutive pulses. The input electronics provides the capability to stimulate each sensor to determine its functional status during ground checkout. Analog parameters from the output electronics and the power supplies are routed to the input electronics for self test purposes. Data flow of the critical engine sensors is such that one element of a redundant pair is routed to the channel A input electronics and the other element is routed to channel B. This arrangement allows continued access to all engine critical parameters even in the event of a total failure of one of the input electronics channels.

Output Electronics - The output electronics interfaces the controller with the propellant valve actuators, the spark ignitors, and the pneumatic on/off solenoids. A single digital to analog converter is multiplexed to five sample and hold circuits, each of which provides position command to a propellant valve actuator servovalve. Each actuator has a primary and secondary servovalve which is selectable by controller discrete output. Discrete output drivers are provided to control each pneumatic solenoid and spark igniter.

Power Supply - All engine electrical power passes through and is managed by the controller. The orbiter supplies the controller with 115 VRMS, 3 phase 400 hz, power which the controller converts into the various dc voltage levels required for operation. The two power suppliers are completely separate, one for each controller channel. Each power supply is furnished power from a separate source in the orbiter. With this arrangement, loss of a single electrical power bus or controller power supply does not affect engine operation. Total loss of electrical power will result in the pressure-ladder sequenced pneumatic engine shutdown previously discussed.

REDUNDANCY MANAGEMENT AND FAILURE DETECTION

The normal operating mode for the controller (Figure 6) is with the channel A computer in control, input data being accessed through both channel A and B input electronics and output control through output electronics channel A. The channel B computer is operating in a ready stand-by-state in order to assure immediate control in the event of a failure of the channel A computer.

CONTROLLER FUNCTIONAL ORGANIZATION

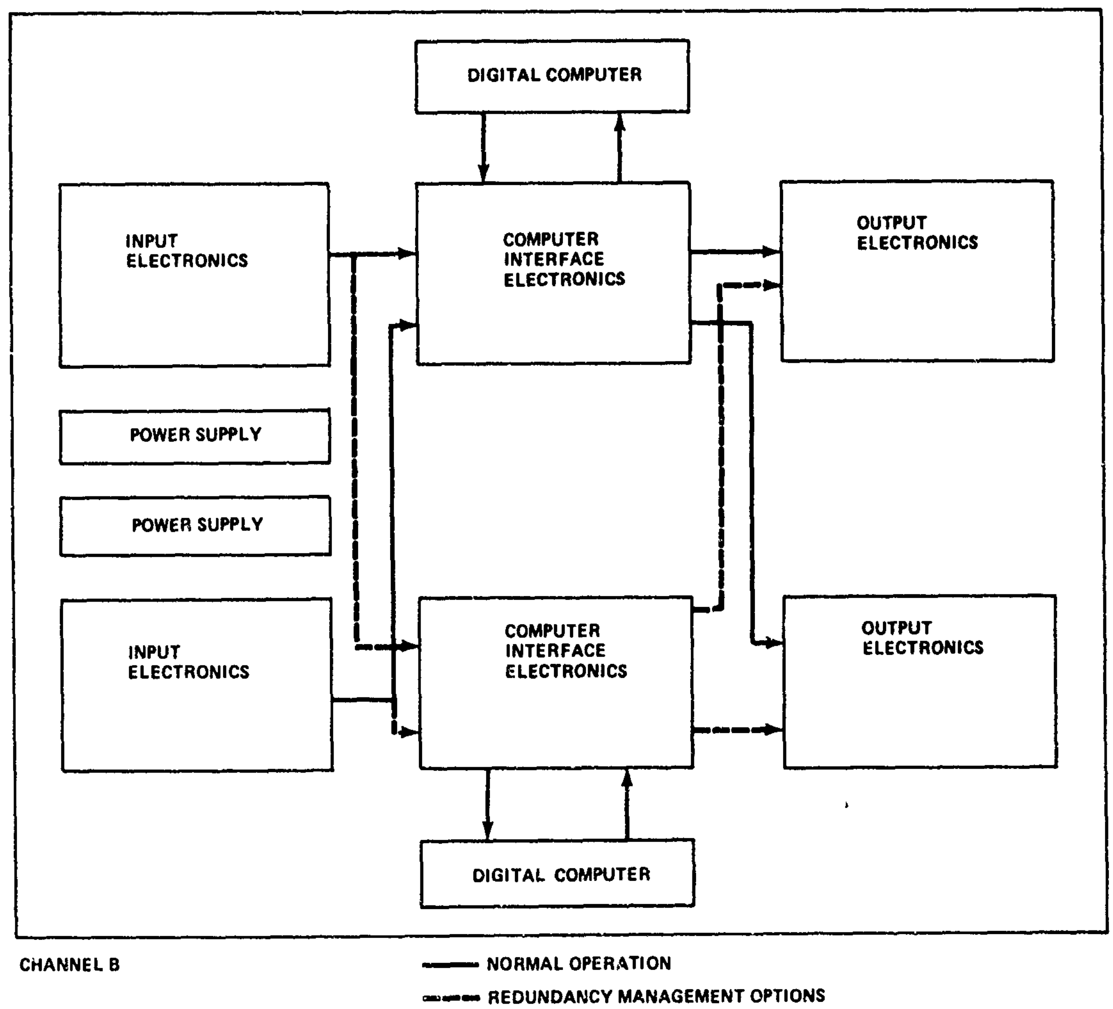

FIGURE 6

The same software is resident in both computers. The channel B computer, when not in charge, is able to track the operation of the channel A computer since it also receives the orbiter commands and the same input data as the channel A computer. There is minimum electrical interface between the two computers in order to ensure that no single point failure exists which could cause failure of both computers.

The channel B computer is prevented from taking charge by a "Watch Dog Timer" (WDT). This device consists of a set of electronic timers which must be reset in the correct sequence each software major cycle (20 milliseconds). Should the channel A computer not properly perform this function, the WDT will timeout, thus placing the channel B computer in charge. The channel B computer also has a set of Watch Dog Timers which if not properly managed will halt the computer.

The software can manage the WDT only if the computer self test is successfully executed. This self test is in the form of a sample problem which exercises all the computer instructions and parity detection capability. The self test is executed every major cycle (20 milliseconds).

The controller has "built-in test equipment" (BITE) points that are sampled by the software such that the full operational status of the controller is verified every 20 milliseconds. Should a fault be detected, the software ceases using the failed element and activates the redundant element.

For example, should the address decoder in the channel A output electronics fail an echo check the software effects an immediate retry. Should this also fail, the channel A output electronics would be declared failed, control would be switched to output electronics channel B, and engine operation would continue, unaffected by the controller electronics failure. The failure of the output electronics would be reported to the orbiter so that it would be known that repair of the controller will be required when the mission is completed.

The controller also provides for failure detection of the elements of the control system external to the controller. Where possible, the controller interfacing electronics is designed such that the most probable failure mode of a device (usually an open or a short circuit) causes an unreasonable value to be read for this device. The software logic detects this out of specification "strike" and does not utilize the input from that device for the current computation cycle. Should this device strike 3 consecutive times it will be declared failed and permanently disqualified. In normal operation the outputs of a dual redundant pair are averaged to provide the parameter data. In the event of a failure of one element, the parameter data is still available from the other element and engine operation continues unaffected. As previously discussed, degraded engine operating modes are provided by the controller/software in the event of total failure of a critical performance parameter.

CONTROL SYSTEM INTEGRATION

The SSME control system just described is a complex hardware/software system. Extensive analysis and testing has been necessary in order to develop and verify the control system hardware/software implementation. The majority of the control system testing has been accomplished in a simulation laboratory. This laboratory employs actual flight configuration control system hardware (controller, sensors, actuators, and etc.) interfaced to a hybrid analog/digital real time engine system simulator. The simulation laboratory provides the capability to verify proper control system response and redundancy management actions when presented with off-nominal engine performance and hardware failures.

This simulation laboratory provides a high fidelity test bed which allowed detailed integration testing of the control system prior to use in actual SSME engine test firings. Since the initiation of engine test firings, the Simulation Laboratory continues to be extensively used for software verification. All software, including changes, is verified in the Simulation Laboratory prior to release for engine use.

FIELD EXPERIENCE

The SSME Digital Control System has been utilized for all engine test firings. As of this writing, 15 different SSME's have accumulated a total of 500 test firings and over 50,000 test seconds.

As the SSME system has matured through this test program, several control system requirement additions and changes have been made. The flexability provided by use of a fully programmable digital computer has allowed the majority of these changes to be accomplished by software modification. This has allowed rapid change incorporation and verification (through use of the Simulation Laboratory) with only minor perturbation to engine test schedules.

The large amount of "in use" experience has demonstrated that the basic concept of a digital control system for the SSME as well as the hardware/software implementation of that system is sound and capable of fulfilling the operational requirements which have been previously discussed.

CONCLUSION

The performance requirements of the Space Shuttle Main Engine coupled with the requirement for fail operational/fail safe capability during all phases of engine operation dictated a control system design that is unique to large rocket engines. The control system is implemented as a fully programmable digital system which has full control authority during all engine operational modes. The controller performs automatic checkout of itself and the engine, and controls engine start, mainstage and shutdown. The controller monitors critical parameters to determine operating condition. If an anomaly is detected, the controller attempts to keep the engine operational by switching to a redundant system or by providing degraded operating modes. In the event continued engine operation cannot be maintained within redline limits, the controller shuts the engine down if enabled by the orbiter.

DISCUSSION

R.L.De Hoff, US

(1) Are the two digital processors running asynchronously?

(2) If so, have you observed switching transients during processor failures at critical operating conditions, e.g. rapid thrust maneuvers, start up, shut down, etc.?

Authors Reply

(1) The two computers are not in sync – The channel B computer is able to track the channel A computer within the same major cycle since both computers receive the same input data and orbiter commands.

(2) There are switching transients they are minor, however, during steady state or thrust changes (thrust change is slow-limited to 10%/sec maximum) Computer switch over and regaining full and stable control takes approximately 80 ms.

There are times during the engine start sequence in which a switch of computers or output electronics cannot be allowed since the transient will likely cause turbine damage The failure response during this time period is engine shut down rather than redundancy switching.

R.Smyth, Ge

What type of information is given to the crew in space shuttle to monitor engine performance and operation?

Author's Reply

The crew is provided with the engines thrust in %, i.e. 90%, 100% etc. and operating status either

normal mainstage
– electronic lockup
hydraulic lockup
shut-down

The crew is provided with the capability to command the engines to inhibit its limit exceeded shutdown. Launch mission rules allow the inhibiting of engine limit shut down under certain emergency conditions.

R.Lo, Ge

Using chamber pressure for calculating oxygen flow rate requires detailed combustion efficiency information (e g. $\eta_{C^*} = f$ (total thrust). Is the latter constant enough to rely on it? For instance, would not the system interpret an injection head failure as a change in oxygen flow?

Author's Reply

The C^* efficiency of the engine is known within certain bounds by design.

Actual C^* as a function of power level is determined by engine calibration firings. This curve as a function of power level is used by the software to calculate liquid oxygen flow. Should a malfunction occur in the engine system which affects C^* this can be noted by a change in the engine operating balance. Limits are placed on the control system authority to prevent an occurence of this type from driving the engine into an over temperature shut-down.

J.F.Evans, UK

Could the author please explain how they achieved adequate confidence that the watch dog timer would detect a faulty computer. What actual probability of undetected computer failure remains?

Author's Reply (Post meeting)

The "WDT" is actually a "dumb" timer which if not properly managed will time out in 20 ms and halt its associated computer To keep the WDT from timing out the software must sequentially access the timer only during several key "gate" times within the 20 ms major cycle The software manages the WDT in correct sequence as a result of successfully passing an increment of the computer self-test program The instruction set for management of the WDT is not contained in one series of locations but rather is scattered throughout memory. This makes the probability of a computer gone "wild" yet keeping itself alive by properly managing its WDT, Nill.

The computer self-test program provides greater than 95% coverage.

H Austin Spang III, US

(1) What type of memory is used? Is it read only?

(2) Does each computer check the other or is it only based on watch dog timer?

Author's Reply

(1) The memory is read/write NDRO mechanized in form of 2 mil plated wire as the storage element.

(2) The channel A and channel B computers do not test each other. Each computer performs a comprehensive self-test each major cycle. The successful completion of this self-test allows that computer to manage its watch dog timer. Please see page 9 of my paper, the first few paragraphs, for a more detailed discussion.

T.O'Brien, UK

How are common mode failures avoided in the software? Is the redundancy provided similar or dissimilar?

Author's Reply

Both computers contain the same software.

Very extensive Failure Mode Effects Analyses are conducted by Hardware/Software systems personnel (not the software designers) to detect the presence of any single point failures. In addition extensive software testing is performed which includes failure injection to verify that no single point failures exist.

B.J.Cocking, UK

Could you please give details of your sensor validation techniques?

Author's Reply

Reasonable limits for the fuel flow measurement are calculated as a function of currently measured thrust. By measuring Main Combustion Chamber Pressure and knowing that the engine mixture ratio is 6.0 one can then calculate the approximate value that fuel flow must be. An additional tolerance is added to this calculated value and it then becomes the upper and lower reasonable limit for the fuel flow meter for that major cycle.

M.J.Joby, UK

(1) Please describe the circuit board interconnect system employed.

(2) In the event of a detected system failure, are any means of locating and recording these faults provided?

Author's Reply

(1) The interconnection between the printed circuit cards is mechanised by a discrete wire system similar to wire wrap. The system used is "stitch welding". The discrete wires are # 30 size nickel and are "spot" welded to a stainless steel terminal by an electrical discharge.

(2) Yes every possible failure has a failure code assigned. When a failure is detected its failure I.D. and parameter value is telemetered as well as stored in computer memory.

EXPERIMENTAL FULL-AUTHORITY DIGITAL ENGINE CONTROL ON CONCORDE

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SUMMARY

The paper describes what is believed to be the first-ever flight standard full-authority digital engine controller. Initial design commenced in 1971 and flight trials were conducted in 1976.

As well as the existing dry engine control and monitoring functions, the controller incorporated reheat control, fault recording and ground-check, and fitted into the same volume as the existing analogue dry engine controller. Particular emphasis is given to computer monitoring techniques and the production of high-integrity software.

1.0 INTRODUCTION

Work on full-authority digital control for gas turbines was started at Rolls-Royce Limited Aero Division, Bristol (then Bristol Siddeley Engines Ltd.) in 1963 and resulted in the first demonstration of this type of control in the U.K. in 1965.

The demonstration was of control of a single-spool engine, and subsequent work resulted in demonstrations of control of more complex engines and also features such as self-test and on-line fault detection.

By 1970 the capabilities of digital computers for full-authority gas turbine control were widely appreciated, but it was doubted that digital controllers could compete with analogue controllers in actual flight applications. By this time, however, the technology had advanced sufficiently for a flight demonstration to be contemplated, and in 1971 a collaborative exercise involving Lucas Aerospace Ltd., the British Ministry of Defence (Procurement Executive), and Rolls-Royce Ltd. Aero Division was launched.

The Concorde aircraft was selected as the most likely demonstration vehicle as its Olympus 593 engines already had analogue electronic controllers. Hence it was convenient to configure the digital controller as a direct plug-in replacement for the existing controller, providing both a flight demonstration and a direct comparison with an analogue controller.

Lucas Aerospace Ltd. were to provide the hardware and Rolls-Royce Ltd. Aero Division, the software.

In the event the first flight took place in July 1976 on board Concorde 202.

2.0 CONCORDE POWERPLANT CONTROL SYSTEM

The dry engine control system comprises two control lanes. In this configuration one lane controls the engine, the other lane being switched off. If a fault occurs in the working lane it is automatically detected by the lane's own self-monitoring arrangements. If the fault persists the lane automatically depowers and the second lane automatically resumes control.

Each lane has its own actuators, the mechanical drives being consolidated via differential gearboxes to control the engine fuel-flow and primary nozzle area. The reheat control is simplex, driving one actuator to control the fuel-flow.

3.0 OBJECTIVES

The broad objectives were to :-

a) Provide dry engine control identical to that provided by the analogue controller.
b) Detect transducer faults at least as well as the analogue controller.
c) Detect a very high proportion of internal faults.
d) Record all detected faults, whether transient or permanent.
e) Incorporate ground check with very little additional hardware.
f) Provide reheat control (normally a separate unit on Concorde).
g) Fit into the same volume (ARINC $\frac{1}{2}$ ATR Long) as the analogue dry engine controller alone.

The objectives were all met, although the reheat control was not test-flown because of equipment configuration limitations.

The completed controller had sufficient unused capacity to have incorporated some other function such as engine life recording, which requires only about 400 words of computer store and 1mSec. run-time to calculate low cycle fatigue and creep damage.

4.0 INTEGRITY REQUIREMENTS

The Civil Aviation Authority has laid down the Concorde integrity requirements (TSS 1). These requirements, taken in conjunction with the relevant British Civil Airworthiness Requirement (BCAR Paper No.484), lead to the following conclusions :-

a) The in-flight shut-down rate due to electronics failure should not exceed 2.3 x 10^{-6} per engine-hour.
b) The upwards runaway rate due to electronics failure must not exceed 10^{-6} per engine-hour. (This figure takes account of the independent overspeed limiter).
c) The downwards runaway rate due to electronics failure should not exceed 2.7 x 10^{-6} per engine-hour.

The above conclusions assume independent failures in the electronics.

This assumption does not apply to the software which, in a fully digital installation, could be common to all lanes, both controlling and standby. In that case, and as software errors have undefinable effects, such errors must not cause a failure rate greater than 10^{-8} per engine-hour. Unlike hardware, software does not have a true failure rate - it is either always faulty or always good, although a fault may remain dormant for a long time. However, it is extremely unlikely that such a fault would remain dormant for 10^8 hours, and thus the final conclusion is :-

d) In this type of system there must be no software errors - the computer programs must conform to the specifications for all combinations of inputs.

5.0 HARDWARE

5.1 Overall System

The system (shown in Fig.1) was, apart from the computer monitor, a simple arrangement using standard circuitry for signal conditioning, multiplexing, analogue/digital conversion etc. connected to the computer via a bi-directional highway. Most of the circuitry is not, therefore, described in detail.

5.2 Inputs/Outputs

The control required 20 variable inputs, 18 discrete inputs, 3 actuator drives, one variable d.c. output and 14 discrete outputs.

The variable inputs were a mixture of thermocouple, resistance bulbs, 2.3 KHz and 400 Hz amplitude-modulated signals, very low frequencies (down to 8 Hz) and two higher frequencies (up to 6 KHz) which were both converted directly to digital form.

The actuator drives were simple pulse drives counting out the number of cycles of 400 Hz demanded by the computer to 2-phase induction motors.

In addition to the control requirements there was a 400 Hz amplitude monitor (used by the computer to compensate 400 Hz transducer readings), a 400 Hz current monitor, two D.C. levels to monitor the performance of the analogue/digital converter, a D.C. signal to the Reheat Controller and the controls for the Ground Check and Fault Recorder.

5.3 Computer

After a comprehensive computer survey the Sanders Associates Inc. MIP-16 was selected as the most suitable for this application. This computer had a multiple-register architecture and 8192 x 16-bit words of core store. With core store the register-register add time was a nominal 1 μSec. and the multiply time, 4.4 μSec. (It is some indication of software complexity that the total program run-time required more than 40mSec. of the 50mSec. sample period).

5.4 Computer Monitoring

Safety circuits were provided for the computer only, the philosophy being that a well-monitored computer is capable of monitoring the remainder of the system. These circuits are worthy of more detailed consideration, as the integrity of the controller depended entirely upon them. Basically there were three primary safety circuits; a Watchdog Timer, a Store Adder and a Comparator, but for completeness the Sample-Rate Clock is included in the description. A secondary circuit known as a Fault Integrator was also incorporated.

a) Sample Rate Clock (S.R.C.)

This was a crystal-controlled clock which interrupted the computer at 50mSec. intervals. In response to an interrupt the computer addressed the Watchdog Timer before running the next cycle of control.

b) Watchdog Timer (W.D.T.)

This was also a crystal-controlled clock, independent of the Sample-Rate Clock, but instead of interrupting the computer it opened a time 'window' of 0.25mSec, about 0.125mSec. before the S.R.C. interrupt was due. If the computer did not address the W.D.T. within this 0.25mSec. window period, a fault was declared. In addition, a fault was declared if the computer addressed the W.D.T. outside the window, or more than once within it.

The action of the computer in addressing the W.D.T. started a delay of 49.875mSec. at the end of which time the next window was opened, and so the system was self-synchronising in that frequency-drift did not trip the safety.

This sequence is shown in Fig. 2.

The W.D.T. crystal oscillator also supplied the computer's clock (5 MHz), so the combined effect of the S.R.C. and W.D.T. was to check that the computer was supplied with the correct frequency, was not stopped and was not "running wild".

c) Store Adder

To preserve the integrity of the system it was necessary to check the store every

sample period, as the actuators could move a significant distance in two sample periods. Since the 'off the shelf' computer had no parity check, and as there was insufficient time in sample period for the computer to perform a normal store sum-check, a separate arithmetic unit and accumulator were connected to the highway between the store and control processor unit. The function of the arithmetic unit was to sum the machine-code instructions and constants as they were read from the program store area. In the software, every possible path through the total program was 'padded' with dummy instructions such that, regardless of which path was followed through the program, a known fixed total should appear in the accumulator at the end of each sample period. Hence any store fault was detectable before it could have a significant effect.

In order to minimise the additional hardware a 16-bit adder with an 'end-around carry' technique was used, whereby if an addition produced a carry, the carry digit was added into the least-significant end of the accumulator.

d) Comparator

The comparator was required to check the number in the accumulator of the store adder at the end of each sample period. In order to ensure that a comparison actually occurred, the comparator was strobed by the W.D.T. address signal from the computer. (Lack of this address would have tripped the W.D.T. If the number was incorrect a fault declaration was made. This comparator was also used for comparison of partial results in successive sample periods, as described in the Software section.

e) Fault Integrator

If a fault was detected in the existing analogue controller the actuator were immediately locked, or 'frozen', into position. If the fault persisted for about $1\frac{1}{2}$ sec. the controller was depowered and a standby controller switched on. If the fault persisted for less than that time the controller resumed control, but if then the fault occurred a full new $1\frac{1}{2}$ sec. period was started.

In the digital controller this area was designed differently, using an up/down counter which counted up to a 'trip' level (when a fault occurred) four times faster than it counted down to zero (when no fault was present). The effect of this was to retain the analogue system's 1.5 sec. delay for a permanent fault, but if an intermittent fault occurred sufficiently often to significantly degrade the control, the controller would depower after some longer period. For example, if a fault occurred every other sample period, the controller would not depower until after about 4 sec. As the actuators were frozen only during faulty sample periods some measure of control was retained.

With a fault every 5th sample period, no depower occurred but control was not noticably degraded. Hence the system would depower if a series of intermittent faults, sufficient to degrade control, occurred.

The operation is shown in Fig.3, with sample periods exaggerated for clarity.

The complete computer monitoring system is shown in Fig.4.

5.5 Ground Check

Any safety circuit has dormant failure modes, where the circuit fails with no immediate effect but is incapable of detecting faults. Hence such circuits should be periodically checked at intervals determined by the dormant failure rate.

No additional hardware was required to check the safety circuits - the computer was made to simulate the various types of fault and for each one, checked that the actuators were 'frozen', as described in section 6.13.

It was decided to incorporate as many checks as possible on those transducers which could fail undetectably with the engine stopped , for example spool-speed probes. In the case of these probes it was decided to inject a frequency to check for probe continuity. Also, an extra datum was incorporated in the jet-pipe temperature measuring system to enable it to measure over a lower-than-normal range, the intention being to permit a comparison with the intake temperature reading on a cold engine. As none of the other tests required hardware, it can be seen that very little additional hardware was required. These ground checks were known collectively as the 'A' checks, and totalled 35 checks, described in section 6.13.

Further checks, of the fault integrator, final lane depower and lane-change, were necessary. Since these actions initiated audible and visual warnings on the flight-deck, it was decided that they should not be included in the pre-flight check, but should be performed much less often. Thus they were classified separately as the 'B' checks.

The checks were controlled from the front of the unit. A three-position switch, a push-button, a green 'GO' placard, a red 'FAIL' placard and eight light-emitting diodes (LEDs) were provided as shown in Fig.5.

Experience has shown that if no visible effects occur while a ground check is being run, there is some scepticism about whether the tests have actually been performed. In addition, the operation of a push-button should have some immediate visual effect. Hence for both psychological and practical reasons the 'GO' placard was made to flash at about 1/4 sec. intervals and a rapidly changing count was displayed on the LEDs during the 'A' checks. The method of initiating the 'A' checks was merely to place the three-position switch in the 'A' position, depress the 'Ground-Check' push-button and wait until either the 'GO' placard stopped flashing and lit steadily (after about 5 sec.), or the 'FAIL' placard lit. In the case of a fault, a code was displayed on the LEDs to denote the fault site, and the software latched up to prevent further operation. In the no-fault case a further press of the push-button returned the controller to normal operation.

For the 'B' checks the 'GO' placard went out and the 'FAIL' placard lit.

It should be noted that software interlocks were provided to prevent operation of these checks with the engine running.

5.6 Fault Recorder

A clear distinction must be drawn between the Ground-Check and On-Line Monitoring. The Ground-Check was checking only for dormant faults in the safety circuits, and

transducer faults which were dormant with the engine stopped. The On-Line Monitoring computer program described in section 6.8, on the other hand, was aimed at detecting faults which could have had immediate and potentially catastrophic effects on the engine. All such computer-detected faults, whether transient or permanent, were stored as a code in a table in the core store. In addition a count of the number of times the fault occurred was stored with the code, so that intermittent faults could be identified.

The Ground Check controls, with the switch in the PFR (Post Flight Readout) position, were used to display the codes and counts on the 8 LEDs. It was, however, thought necessary to provide a test of the LEDs and GO/FAIL placards prior to displaying the codes. Hence the first 'code' in the table was set to all binary ones, the associated count being the number of times the unit had been switched on. Also, to differentiate between eight- bit codes and eight-bit counts on the eight-bit LED display, both GO and FAIL placards were lit to denote a code, while the GO placard only was lit to denote a count.

In operation, the first press of the Ground-Check button caused the first 'Fault-code of 'all ones' to be displayed, and both GO and FAIL placards to be lit, thus providing a test of all lamps. The next press caused the number of power-ups to be displayed with the GO placard only lit. The third press caused the first genuine fault-code (if any) to be displayed, while the fourth press displayed the associated count. This procedure was followed until all lamps went blank indicating end of readout, the maximum number of codes being 27.

The Fault Recorder did in fact detect a 'sticky' actuator, the associated count increasing more rapidly with each flight until eventually the actuator seized.

6.0 SOFTWARE

6.1 Programming Techniques

6.1.1 Integrity

The very stringent integrity requirement of no software errors necessitates the testing of every possible path through the software. With a program length of over 7 thousand words experience has shown that this is virtually impossible with usual techniques. Unrestrained programming at assembler or machine-code level results in long programs with many paths, frequenctly incomprehensible to any but the original programmer. Such a program is very difficult and tedious to test by forcing the program to run down every possible path, and proving that it has done so. Test documentation is meaningful only to the original programmer and thus virtually useless, while modifications can become extremely difficult. Use of a high-level language is, if anything, even worse than assembler level programming. The compiler itself is likely to have errors in it (experience with compilers in this respect has not been good) and thus the object code must be tested, but without a flow diagram this is an impossible task. The approach adopted by Rolls-Royce was modularity in the form of subroutines. Simple, accurately-defined, non-interactive subroutines at the lowest level were used to build up subroutines at the next highest level and so on (a 'hierarchical modular structure'). In the interests of simplicity the subroutines were single-entry, single-exit, and were also non-recursive.

6.1.2 Basic Subroutines

The subroutines used (Ref. Appendix 1) were a general-purpose set, not engine-oriented, to provide maximum flexibility. To obtain full modularity they were self-linking so that no subroutine calls were required, and they organised their own data transfers. Thus to the user they appeared to be very powerful multi-address machine-code instructions. For example overflow-protected (saturating) addition is written merely as:-

```
ADD   (i.e. Address of add subroutine)
 A    (i.e. Address of addend)
 B    (i.e. Address of augend)
 C    (i.e. Address of sum)
```

This is known as the calling sequence, and is all that is required. The next item in the calling sequence is the address of the next subroutine. Many years experience at Rolls-Royce in the use of this technique has shown that it has many desirable features, among which are :-

a) The calling sequence is machine-independent, providing portability between different machines.
b) The user is relieved of any necessity to organise data in the subroutine's working area prior to subroutine entry.
c) The subroutines can be used to write very complex programs quickly and easily, with a good chance of being error-free prior to testing.
d) Most important for this application, the subroutines can be very thoroughly tested and then used with complete confidence. As an example of testing, the "add" subroutine was specified to produce the maximum positive output for positive overflow and maximum negative output for negative overflow. It therefore had three internal paths, which could in principle have been tested with three pairs of numbers. In practice eight paths were used, four to check 4-quadrant non-overflowing addition and four to check the overflow ranges. A description of the self-linking and data transfer functions used in this type of subroutine is given in Appendix 1.

6.1.3 Functional Subroutines

The basic subroutines were used to build up the functional subroutines at the next-highest level in the hierarchy. These subroutines, described later, were :-

i) Input ; ii) On-Line Monitor ; iii) Reheat Control (Not described, as it was not flown). iv) Dry Engine Control; v) Data Store Test; vi) Branch Test; vii) Output; viii) Ground Check.

6.1.4 Executive Program

At the highest level of the hierarchy, the Executive Program organised data transfers, and called the functional subroutines. In the process, it also organised the double Dry

Engine Control Subroutine runs to provide the fault-detection capability for the Central Processor and part of the Data Store, as described in para. 6.4.

6.2 Program Store Protection

In order to satisfy the store safety circuits, it was necessary to ensure that the binary sum of all constants and machine-code instructions read from the program store during any one sample period was a constant. To achieve this every one of the possible paths through the complete program had to be 'padded' using 'fetches' of appropriate constants. With thousands of possible paths through the control program alone, this might appear to be a difficult task. However, the programming techniques described in the previous section made the task fairly simple, as there were relatively very few paths within each subroutine. It was also easy to decide the optimum positions for the padding constants by inspection, although a formal approach had been devised. It was decided that each basic subroutine should internally add 0001_{16} to the store-adder in the computer monitoring circuitry and the padding constant was obtained as follows :-

i) The sum of the instructions (including the pad 'fetch' instruction) was obtained using a hexadecimal calculator. ii) The carry digits (those in excess of 16 bits) of the above total were 'wrapped around' to match the store adder. For example, if the total had been 12345_{16}, in the 16-bit store adder the '1' would have been added to the least significant digit, giving 2346_{16}. iii) The 4-digit total above was subtracted from 10000_{16} (the desired total 'unwrapped') to give the padding constant. For the above example this is $DCBA_{16}$. When running a program, the calling sequence for the subroutine was also automatically added into the store-adder circuit. Taking ADD as an example again, the calling sequence could be :-

Calling Sequence	Coding
ADD	0200
A	3C00
B	3C02
C	3C04

The total of this calling sequence is $B606_{16}$, and the internal padding of the subroutine (0001_{16}) brings this to $B607_{16}$. In order to pad the calling sequence to the desired total (the comparator was set for $FFFF_{16}$) a special pad subroutine was written. The calling sequence was :-

PAD
K

and its only function was to fetch K from store. In the process, of course, the coding for PAD and the internal padding of 0001_{16} were also added into the store-adder circuit. Padding of the different calling-sequence paths was very similar to padding inside a subroutine. It is estimated that the padding added about 10% to the run-time, a small penalty to pay for nearly 100% store protection. The actual protection is given by :-

$$(1 - 1/2^{16}).100 = \underline{99.998\%}$$

6.3 Data Store Protection

The technique used for program store protection was not applicable to the variable data area. Hence, in order to protect incoming data from store faults, each input was added to a running checksum before being stored. Then, just before the computer sent its output to the actuators, it summed the input data with the Data Store Test subroutine, and compared the result with the checksum. The delayed input data, and lags calculated by the control program, were protected by the same process which provided the Central Processor Unit monitoring, described in para. 6.4.

6.4 Central Processor Unit Monitoring

The usual C.P.U. self-test program, where the computer runs through its instruction repertoire with selected data, was considered to be inadequate by the Civil Aviation Authority, as the degree of protection afforded could not be quantified. Examination of the Dry Engine Control Routine showed that it could provide adequate checking because most instructions were used many times over with virtually random data. Hence if the 46 partial and final results were correct, there was a high and quantifiable probability that no fault was present. Several possible procedures, including a run of the control program with fixed test data every sample period, were examined and the procedure finally adopted was as follows (see also Fig. 6) :-

a) At power-up, read the first set of input data, then run the control program (run 1a), retaining the input data and all partial and final results.
b) Follow (a) with a run of the control program with test input data (Test Run) and check the test results. If these results are good there was no permanent fault during run 1a.
c) On receipt of the next Sample-Rate-Clock (SRC) interrupt, read the second set of input data and run the control program (run 2a), retaining the input data and partial and final results.
d) Follow (c) with a run of the control program using the first set of input data (run 1b) and compare partial and final results with those obtained from run 1a. If they agree, there was no permanent fault during run 2a, and no transient fault affected either run 1a or run 1b.
e) On receipt of the next SRC interrupt, read the third set of input data and run the control program (run 3a).
f) Follow (e) with a run of the control program using the second set of input data (run 2b) and compare partial and final results with those obtained during run 2a. If they agree, there was no permanent fault during run 3a, and no transient fault affected either run 1a or run 1b. This 'leapfrog' process is repeated indefinitely. Because a faulty computer obviously cannot be relied on to declare itself faulty, the comparison is performed in the hardware comparator, described in section 5.4, rather than in the computer itself. The procedure did not fully check the condition staticisers (carry,

overflow etc.) which could fail dormant. Thus a special check of the staticisers, the Branch Test, was incorporated as a separate subroutine. The 'leapfrog' technique also protected all of the Data Store apart from the new data area, as any corruption of data would produce a faulty comparison check.

6.5 Operating System

Clearly, from the testing and padding requirements, the programmers required an intimate knowledge of the numeric coding and could expect little assistance from assemblers and the like. Thus it was decided from the outset to dispense with most software aids, and to hand-code the subroutines and calling sequences in 4-digit hexadecimal format. Although slightly tedious this was not a difficult task, especially as the machine-code for the Sanders computer used 4-bit fields throughout. Paper tapes were prepared on a teleprinter and loaded, via a high speed reader, with a simple hexadecimal loader which was permanently resident in the computer. This loader also checked the characters for parity errors. In order to prevent undocumented software changes, no paper-tape punch was attached to the system, and therefore the store could not be dumped. Hence, although modifications could be entered by hand for test purposes, permanent alterations had to be entered on tape. This was done by updating a master tape, so all modifications were recorded on the teleprinter typeout. It is known that this lack of a pump facility did in fact prevent undocumented modifications. The only software aid used was a program known as the Diagnostic. Controlled by the switches on the Operators Control Panel, it ran one basic subroutine at a time, and could display the address where it had stopped, the result (if any) of the previous subroutine and the cumulative sum of the program store. The Diagnostic proved to be very valuable, as it was possible to step rapidly through long programs, and the paddingwas easy to check.

6.6 Initialisation Subroutine

The purpose of this simple routine was to clear counts, fault markers etc. to obtain correct operation of the other routines on power-up or fault recovery. It also started the frequency-to-digital converters ready for the first run of the Input Routine.

6.7 Input Subroutine

This routine read all inputs including the normal 115V 400 Hz power supply amplitude, forming the running checksum as it proceeded. It then used the power supply amplitude to correct the 400 Hz transducer readings and derived the rates-of-change of the pilots lever angle and jet-pipe temperature, for use in the control program.

6.8 On-Line Monitor Subroutine

The safety philosophy was that the computer should monitor all the variable inputs and outputs, and that a short transient fault should not cause a lane-change. To do this, several different techniques were employed :-

a) Direct Comparison. On Concorde there are two pilot's lever pick-offs per control lane, the outputs of which can be compared.
b) Rate of Change. Most engine and airframe parameters have a rate of change which is limited by physical considerations, for example spool-speed rates are limited by inertia. Thus if a reading changes faster than physically possible then that reading is recognisable as faulty.
c) Out of Range. A reading is obviously faulty if it is outside the possible range of that parameter.
d) Indirect Comparison. The two spool-speeds and the jet-pipe temperature are all related, and crude but effective inter-comparisons can be made. Caution is, however, necessary as it was discovered that if an engine is shut-down in flight it can windmill at high RPM while the jet-pipe temperature drops rapidly towards zero.
e) Sign Correlation. This technique was used to check the actuators - the actuator velocity pick-offs should normally follow the actuator drives. Because of actuator overshoot under certain conditions, however, the tolerances and limits proved to be extremely difficult to set up, although satisfactory operation was eventually obtained. This is, perhaps, an area where hardware fault detection would be more suitable with this type of actuator. A further point about the actuator safety is that if a fault is detected, of necessity the actuator is frozen. Therefore, in order to recover from a transient fault the actuator must, after a short delay, be unfrozen and tried again. A unique code was assigned to each of the 27 possible fault sites and each time a fault was detected the appropriate code was stored in a table, and an associated count incremented by 1. This code was later retrieved as explained in para. 6.4.

6.9 Dry Engine Control Subroutine

One of the conditions of flight clearance for the digital controller was that it should not adversely affect the normal development flying of the aircraft (Concorde 202). Thus the analogue unit's control functions and test procedures were copied as closely as possible, even though this approach did not fully exploit the potential of digital control. Development of the Olympus 593 and its control laws had, by 1976, resulted in a very complex control system. Although lack of space precludes a detailed description some idea of the complexity can be gained from the fact that there were 25 individual control loops associated with the fuel-flow control, and 9 more loops associated with the primary nozzle, together with the associated selection logic. Most of these loops were themselves quite complex, with non-linear multi-parameter schedules, and considerable interaction between them.

6.10 Data Store Test Subroutine

This test, performed immediately after the first run of the Dry Engine Control Subroutine, was incorporated to ensure that that program had been run with correct data. This subroutine summed the input data and compared this sum with the running checksum formed by the Input Subroutine. In this particular case it is permissible to perform

the comparison within the computer - if the Central Processing Unit is faulty the worst it can do is to declare a non-existant data store fault. A persistent Central Processor Unit fault would, in any case, be detected by the 'leapfrog' technique described in para. 6.4 or by the Branch Test subroutine, para. 6.11.

6.11 Branch Test Subroutine

The staticisers (sign, overflow, carry, non-zero) upon which the conditional branch instructions operate, may remain in one state for several sample periods. Hence, if one of them fails without changing state the fault will not be detected by the 'leapfrog' technique. This subroutine therefore set the four staticisers to all possible 16 conditions, and, for each condition, tested all 18 conditional branches in the computer.

6.12 Output Subroutine

Considerable difficulty was experienced with the actuator velocity drives, which had only 20 quantisation levels. This resulted in a very high apparent gain across the actuator, requiring a corresponding very small gain (a nominal -1/16th) in the computer. If this gain is plotted as shown by the solid line in Fig.7, it can be seen that there are large discontinuities and a deadband. It was found that the actuators tended to become 'trapped' in the notch at 23 bits control output, tripping the On-Line Monitor program. Thus the gain curve was modified as shown by the dotted line, which provided a satisfactory solution. The effect of the deadband was beneficial on most of the control loops; it was small enough to provide satisfactory control while at the same time it prevented actuator 'jitter'. However, it was too large for the jet-pipe temperature limiter, where the deadband was 28°C. The solution adopted was to arrange that when this loop entered the deadband the gain was switched from -1/16th to -1, with a very slow actuator velocity limit imposed. This resulted in the limiter loop cycling slowly by about ±1°C around the required datum - well within tolerance.

6.13 Ground Check Subroutine

The Ground-Check was controlled, as described in para. 5.5, by a three-position switch labelled 'A', 'PFR' and 'B', eight light-emitting diodes (LEDs), a green 'GO' placard and a red 'FAIL' placard mounted on the front of the unit. Previous examples of ground-check had run the program at base level, the sample-rate-clock and safety circuits being serviced by a dummy interrupt routine. This practice was thought to be potentially dangerous for a flight system - a situation can be envisaged where the computer is running incorrectly at base level, while correctly servicing the safety circuits at interrupt level. Hence the Ground-Check program was time-slotted and run at interrupt level. It was, therefore, also necessary to pad the program as described in para. 6.2. During previous demonstrations of ground-check the comment had been made that 'there's' no proof that it's doing anything. Hence, on this system the eight LEDs were made to count up rapidly, while the green 'GO' placard flashed slowly. This appeared to constitute proof that the system was, in fact, checking itself as no adverse comments were made. The primary function of the ground-check was to check the safety circuits for dormant faults, but as a demonstration that the system could check itself, other tests for faults which would be dormant before the engine was started were incorporated. On a commercial aircraft these could perhaps be performed before passenger embarkation. The best test of the safety circuits was to check that they could 'freeze' the actuators. Hence, in order to differentiate between actuator faults and safety circuit faults it was necessary to first check the actuators for correct movement. The actual checks were as follows :-

a) 'A' Checks

i) Drive actuators closed onto end stops to establish a datum.

ii) Check position pick-offs for end-stop position.

iii) Drive actuators open, checking position and tacho pick-offs against each other.

iv) Drive actuators nearly closed, again checking position and tacho pick-offs.

v) Activate each safety circuit in turn, checking that when activated the actuators cannot be driven, and that when de-activated they can be driven (allowing sufficient time between checks to allow the fault integrator to count down).

vi) Operate relay to inject test frequency into spool-speed probes (continuity check) and check frequency-digital converters (accuracy check). Release relay and check that test frequency is removed.

vii) Check T1 (intake temperature) and TJ (jet-pipe temperature). Originally it was intended to compare T1 and TJ, but as there was a possibility of the engine being hot when testing, a 'credibility' check was used.

viii) Store sum-check.

b) 'B' Checks

Activate a safety circuit and start a software timer. Check that the timer does not reach 1.5 sec. If it does, either the fault integrator or the final depower relay is faulty. In the interests of safety, software interlocks were incorporated to prevent testing if the engine was running, or to abort testing if the engine was started during a test.

6.14 Fault-Code Readout

For convenience, the fault-code readout was incorporated in the Ground-Check subroutine. All 27 possible fault-sites were allocated a unique code, and whenever a fault was detected the code was stored in a fault table and an associated count incremented. This permitted information to be stored about permanent, transient and intermittent faults. To distinguish between fault codes and counts on the 8-bit LED display (Fig.5), both 'GO' and 'FAIL' placards were illuminated for a code, while for a count the 'GO' placard only was lit. In addition a power-up was claddified as a 'fault', the fault-code being all ones (to test the LEDs). With the 3-position switch in the 'PFR' (Post-Flight Readout)

position, a press of the 'Ground-Check' push-button caused the computer to search the fault-code store. The first code encountered was the all ones power-up code, causing all 8 LEDs, the 'GO' and 'FAIL' placards to be illuminated. The next press of the button caused the number of power-ups to be displayed, with only the 'GO' placard lit. Further presses caused further fault-codes and counts (if any) to be displayed until all lamps were extinguished to indicate 'end of readout'.

7.0 FLIGHT CLEARANCE

It was not possible to dedicate the British development aircraft, Concorde 202, to flight trials devoted solely to the controller. Firstly, the cost would have been prohibitive and secondly, the aircraft was being used intensively for other purposes. Permission to fly the controller, on a 'free-ride' basis, was granted only on condition that it did not interfere with the aircraft's normal development flying. Thus it was vital that the controller performed exactly as the existing analogue system and that it did not produce radio frequency interference. It was also important that the controller should not fail, due either to radio frequency interference from other equipment or to an internal fault. Hence the appropriate parts of the normal tests for avionic equipment were applied. One of the three controllers was subjected to severe temperature cycling and vibration tests, followed by a strip-down and visual check. Of the other two, one was subjected to EMC (Electro-Magnetic Compatibility) tests, and both received R.S.T. (Reliability Shakedown Testing). No problems were encountered during testing, even the EMC tests being passed easily. This was rather surprising in view of considerable pessimism in many quarters concerning the vulnerability of computers to radiation, and was presumably the result of good design. One unit was subjected to bench pass-off tests on a rig used to pass-off the analogue controllers. This cleared it to run an engine on a test-bed, where it was subjected to an exhaustive series of tests to clear it for flight.

8.0 FLIGHT TRIALS

The flight-cleared controller has, to date, completed some 25 hours of flying and approaching some 100 hours of engine running on seven different engines. Despite all the careful testing, three minor initial problems appeared on the aircraft. These were :-

i) On changeover from aircraft to ground power, the unit was subjected to an unexpected transient power interrupt, with a very slow voltage recovery. This corrupted the core-store contents, which resulted in the safety circuits operating and changing lanes. The fault was found to be due, not to the core-store itself, but to an error in the power-up sequencing which had not been revealed by the bench power-interrupt tests. It is of interest to note that no problems were encountered with the core-store. In fact, the power-up sequencing error was the only hardware fault encountered during all the engine running and flight trials.

ii) The HP spool-speed signal on the aircraft was noisier than on the test-bed. The only result of this was an occasional flicker of the auto-ignition, which was easily cured in the software.

iii) During an engine relight test on the edge of the relight envelope, the engine took a considerable time to relight. Just before relight the 'TJ FAIL' placard on the flight-deck flashed. Such a failure is not serious, as the controllers continue operation in this condition. This problem was traced to the software intercomparison of N_H, N_L and T_J. Although normally a good test of T_J, it had not been appreciated that the engine could windmill at very high RPM with a very low (nearly down to 0^oC) jet-pipe temperature. This test was deleted, reliance being placed on the existing out-of-range test. Apart from these minor teething problems, the unit has been flown over most of the flight envelope of the aircraft with no further problems. During the flight trials the Fault Code Readout revealed an intermittently-sticking nozzle actuator, the fault-count increasing more rapidly with each flight. At the time it was not certain if there was a genuine fault or if the safety was over-sensitive. The digital controller was therefore moved to another engine, where the fault disappeared. Subsequently the original actuator seized-up and had to be changed. This experience revealed the potential usefulness of the Fault-Code Store. The unit has also been used twice to assist in engine development. The requirements, impossible to meet manually, were in addition to the normal control funtions but were readily incorporated in the software, no hardware changes being required.

9.0 FUTURE TRENDS

9.1 Computer Monitoring

The advent of microprocessors and high-density stores has rendered the monitoring techniques employed in the controller obsolete. Current thinking is that, at least for military applications, a microcomputer can be monitored by another, identical microcomputer running in exact synchronisation. If a microcomputer with serial unidirectional highways is used, then the input highways can be paralleled together, to ensure that both microcomputers receive the same data. All that is required on the output highways is a one-bit comparator. Of course, a device such as a watchdog timer is still required for common-mode faults such as clock failure. A system of this type has been built and soak-tested for over 1000 hours with no problems at all, although subsequently a self-synchronising feature was added to permit recovery from possible transient loss of synchronisation. For civil applications it is likely that the airworthiness authorities will insist on dissimilar microcomputers. The same technique can still be applied, but is considerably more complicated.

9.2 Failure Detection and Survival

Traditionally, engine controllers have consisted of two separate lanes of control. In any one lane it is not possible to detect some forms of fault, (for example drift), and full use is not made of the available redundancy. If, however, the highways of a

digital system are interconnected through suitable electrical isolators as shown in Fig. 8 then the controlling computer has access to both sets of transducers. Consequently it can detect all previously undetectable faults by direct comparison and, although in these cases it cannot locate the faulty transducer, it can store a fault-code and use some predetermined failure strategy, depending on the aircraft type. For example, on a vertical take-off/landing aircraft it can use the reading giving the highest thrust, or on a multi-engines aircraft it could fail frozen and warn the crew, who can take appropriate action. The availability of both sets of transducer readings also improves failure survival. In previous systems a failure in the controlling lane followed by another in the standby lane resulted in system failure. With the interconnection, however, the only faults which fail the system are those of identical pairs of elements, e.g. a pair of transducers, a pair of computers etc. Typically, this feature improves failure survival by some 5 - 10 times.

9.3 Simplex and Triplex Functions

On many systems, simplex functions such as reheat are required. These are readily accommodated in the highway interconnections as shown in Fig.9. Future engine control systems will probably be required to interface with triplex highway systems. Obviously, with three electrically isolated sets of inputs and outputs, no difficulty would be experienced with this type of system.

9.4 System Survivability

The interconnected arrangement has the advantage that it can, if required, be physically separated into two units, or three with reheat, thus enhancing survivability from battle-damage and fire.

10.0 CONCLUSIONS

So far as is known, this was the first exercise of its kind, and there were no guidelines to follow. Thus the emphasis was on caution and, above all, simplicity. The use of interrupts (other than the Sample Rate Clock) and Direct Memory Access was avoided, as were programming techniques such as multi-sample-rate working and (other than for Ground-Check) time- slotting. It is thought that the success of the project was largely due to this simplistic approach - efforts could be concentrated on the real problems, of which there were many, rather than potential problems introduced by complexity. It is clear that considerable caution is necessary when introducing full-authority digital control - even this system, based on an existing analogue controller, was not entirely trouble-free. The success of the project demonstrated the feasibility, flexibility and capability of digital control. However, as the units were built on an experimental basis, production costs were not known. The subsequent development of microprocessors, of course, has altered the situation considerably; an equivalent system now would undoubtedly be smaller and cheaper than the current analogue system.

11.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of M.O.D. (PE) and Lucas Aerospace, and the invaluable assistance of the Rolls-Royce and Lucas Aerospace project teams.

APPENDIX 1

1A. Self-Linking Subroutine Internal Organisation

The most common organisation, suitable for most machines, is to use a pointer which points to the next required item in the calling sequence. Thus, for example, if the calling sequence is :-

Location	Calling Sequence	Comments
1000	ADD	Address of ADD subroutine
1001	A	Address of addend
1002	B	Address of augend
1003	C	Address of sum
1004	NEXT	Address of next subroutine
1005	X	Data address

then, after entry into the ADD subroutine the pointer value will be 1001. Internally the functions could be :-

Fetch contents of pointer, i.e. A
Increment pointer
Fetch contents of A, i.e. addend
Fetch contents of pointer, i.e. B
Increment pointer
Fetch contents of B, i.e. augend
Perform add function (form sum)
Fetch contents of pointer, i.e. C
Increment pointer
Store sum in contents of C
Fetch contents of pointer, i.e. NEXT
Increment pointer
Jump to NEXT, i.e. enter next subroutine.

On entry into the next subroutine the pointer value will be 1005, the address of the first data address for the next subroutine. Clearly the internal functions can be tailored to suit the abilities of the particular machine; for example a machine could have an instruction which increments the pointer then fetches its contents, in one operation. Initial entry into the calling sequence must set up the correct initial value for the pointer. Frequently the machine's own subroutine call will do this automatically. If not, a special subroutine is necessary.

2A. Subroutine Used

CALLING SEQUENCE	FUNCTION
ADD/A/B/C	Overflow - protected addition
SUB/A/B/C	Overflow - protected subtraction
MULT/A/B/s/C	Overflow - protected multiplication (s = scaling factor)
DIV/s/A/B/C	Overflow - protected division (s = scaling factor)
MOD/A/X	Overflow - protected modulus
NEG/A/X	Overflow - protected negate
SHIFTA/s/A/X	Overflow - protected arithmetic shift(s = shift factor)
VBS/X/TAB/Y	Variable break-point schedule ("function generator")
HWS/TABX/X/TABY/Y	Highest wins (TABX = data address, TABY = associated codes).
LWS/TABX/X/TABY/Y	Lowest wins
INTEG/A/B/s/X	Double-length integrator
SQRT/A/B	Special-purpose square root
SHIFTL/s/A/X	Logical shift
AND/A/B/X	Logical AND
OR/A/B/X	Logical inclusive 'OR'
TRANS/A/X	Transfer (A) to (X)
DELAY/A/X/Y	(A) (X), then (X) (Y)
MOVE/TABX/TABY	Move table X to table Y
SWAP/TABX/TABY	Swap tables X and Y
READ/TAB/J/X	Read jth item from table
STORE /A/TAB/J	Write into jth table place
PASS	No operation
JUMP/L	Unconditional relative jump
JUMPIF/A/B/L1/L2/L3	Conditional relative jump L1 if A B L2 if A = B L3 if A B
JUMPS/TAB/J	Relative jump to jth address in table
SWITCH/X/m/L1/L2	Relative jump to L1 if x m = 0 L2 if x m ≠ 0
SUBR/N/L	Enter subroutine at location L Store link in location N.
EXIT/N	Exit subroutine
SERVICE/t	Response to clock interrupt. Set sample period to t.
WAIT	Wait for next clock interrupt
ADC/a /X	Analogue input from channel a (Right justified)
DAC/X/a	Analogue output to channel a (overflow protected)
ACT/X/n/a	Actuator drive to channel a, limited to n pulses.
CPUSC	CPU staticiser check.
PAD/k	Read k from store.
RCS/SUM	Running Checksum. Add R1 to (SUM).
TCS/TAB/SUM	Table checksum.
COMPT/TABA/L	Compare tables. Jump to L if not equal.

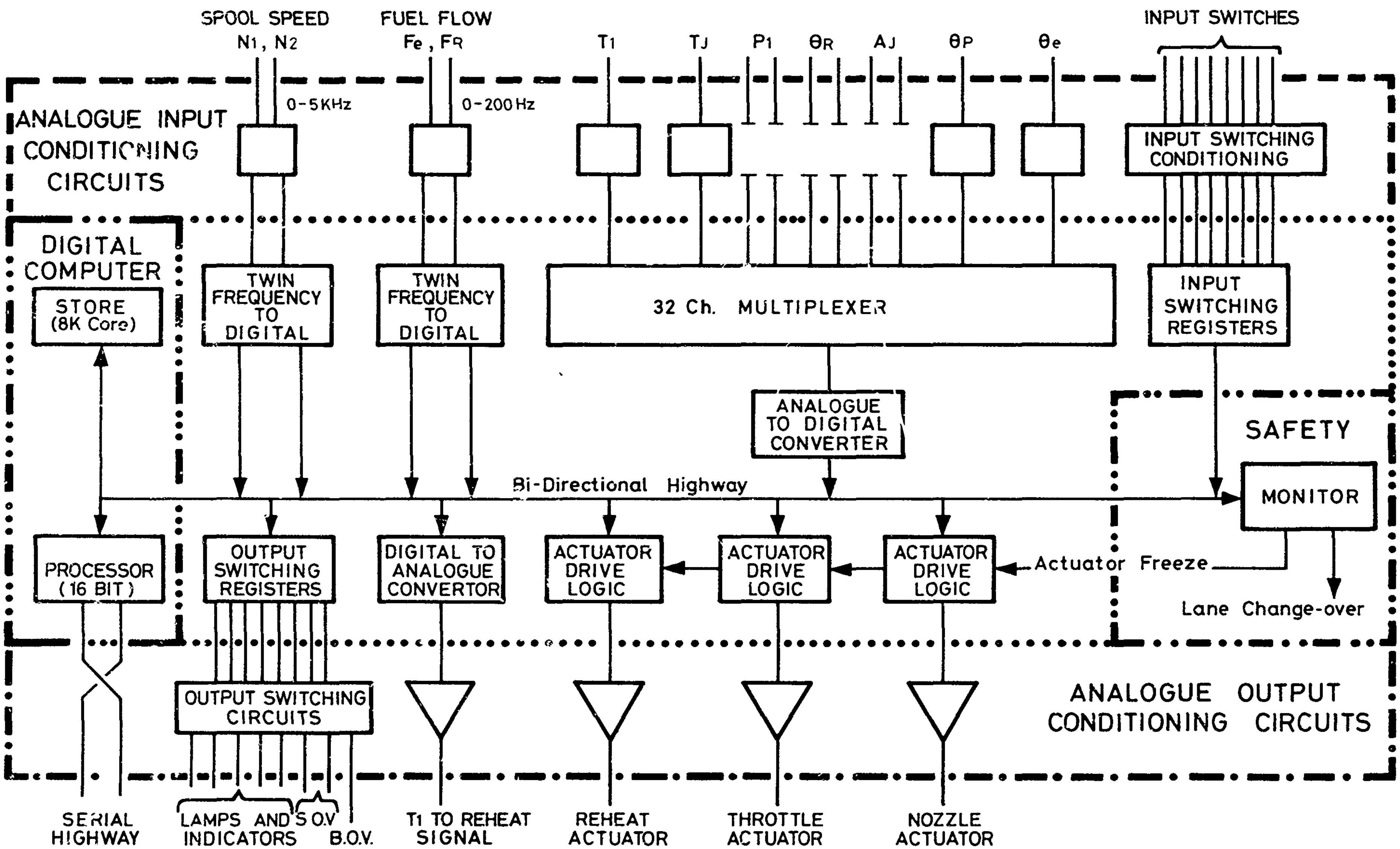

Fig.1 Digital controller

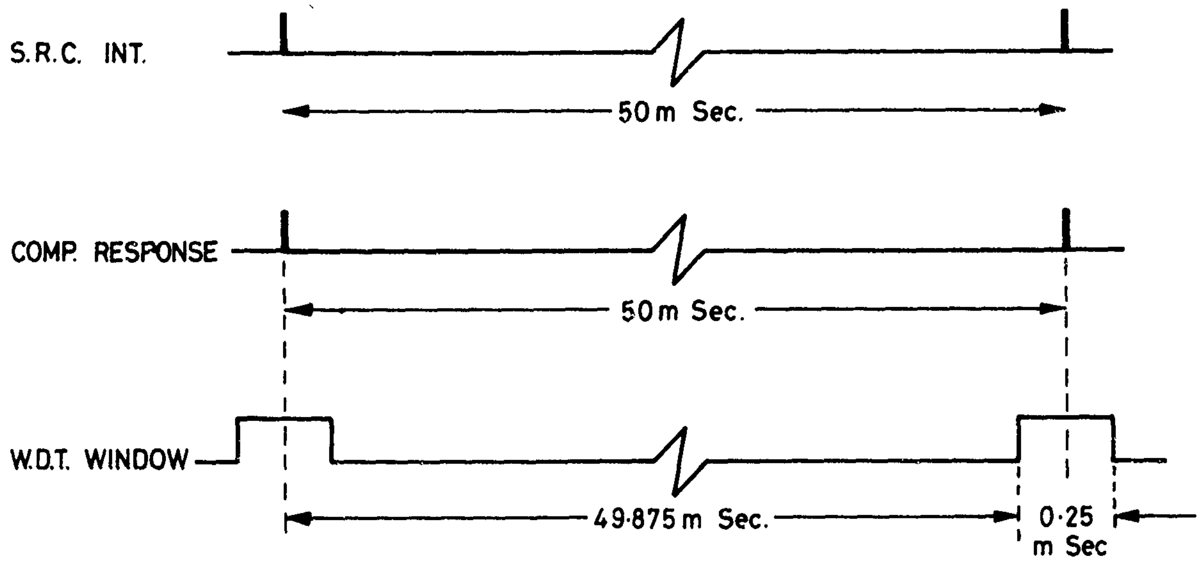

Fig.2 S.R.C. & W.D.T. operation

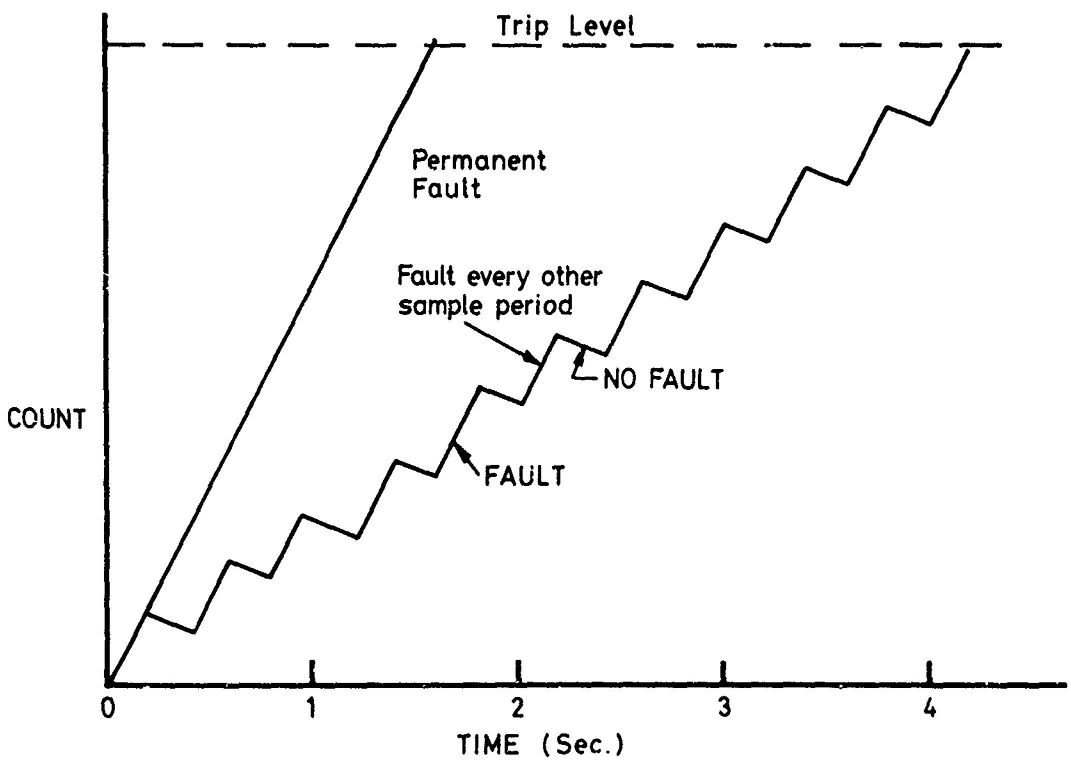

Fig.3 Operation of fault integrator

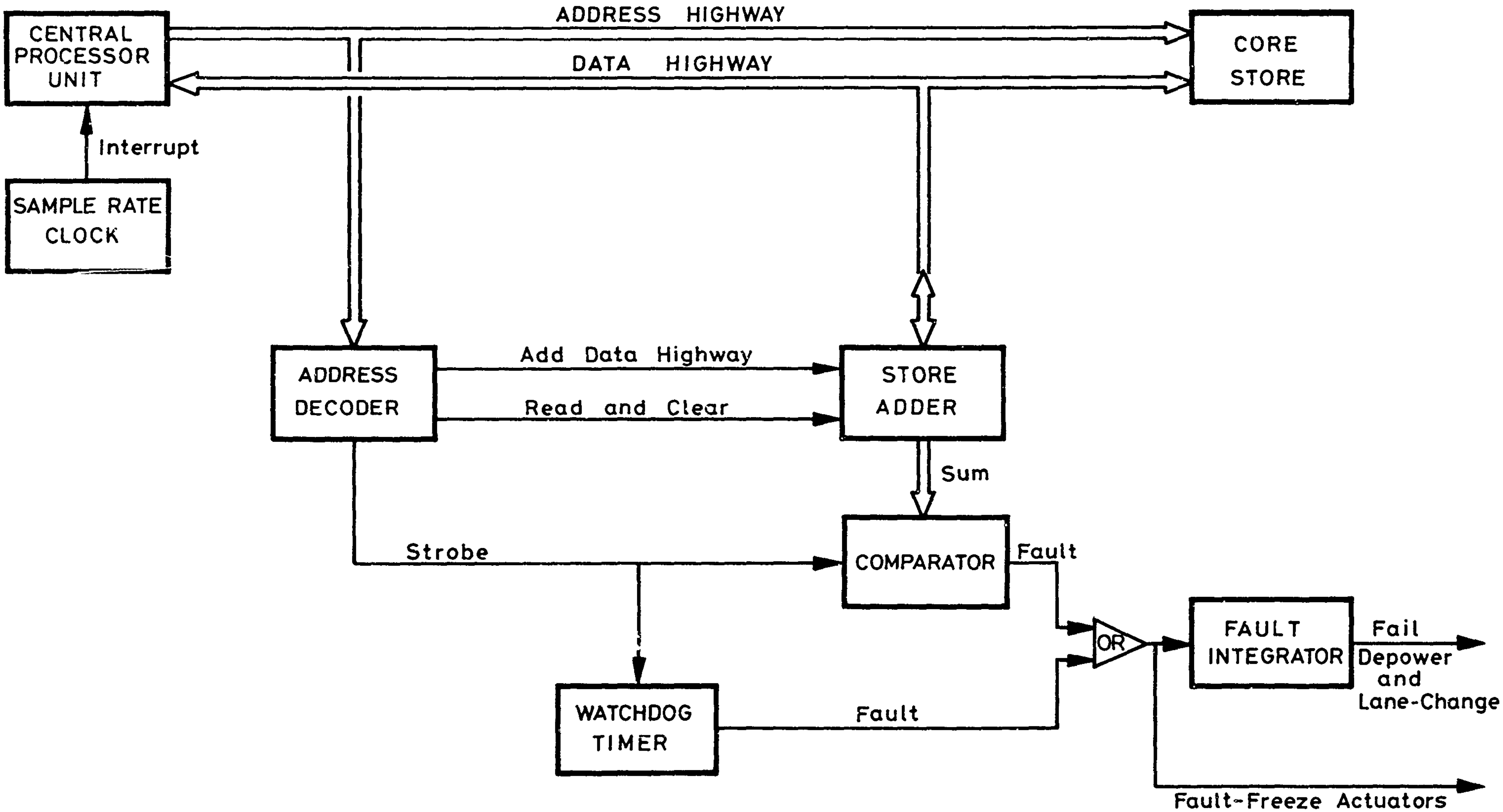

Fig.4 Computer monitoring system

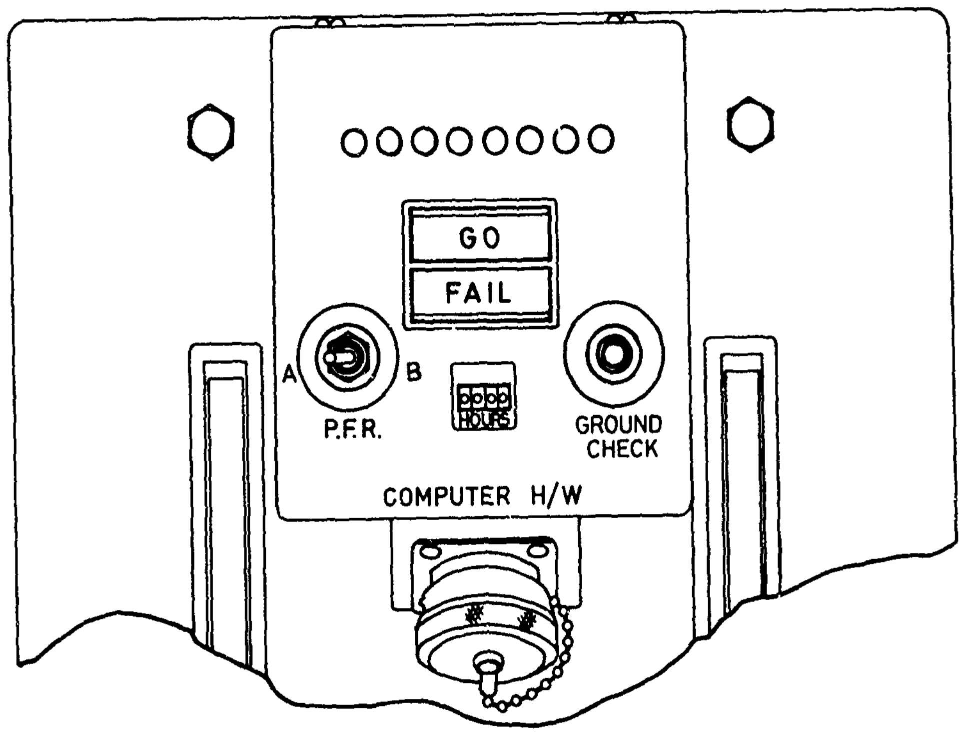

Fig.5 Front view of controller

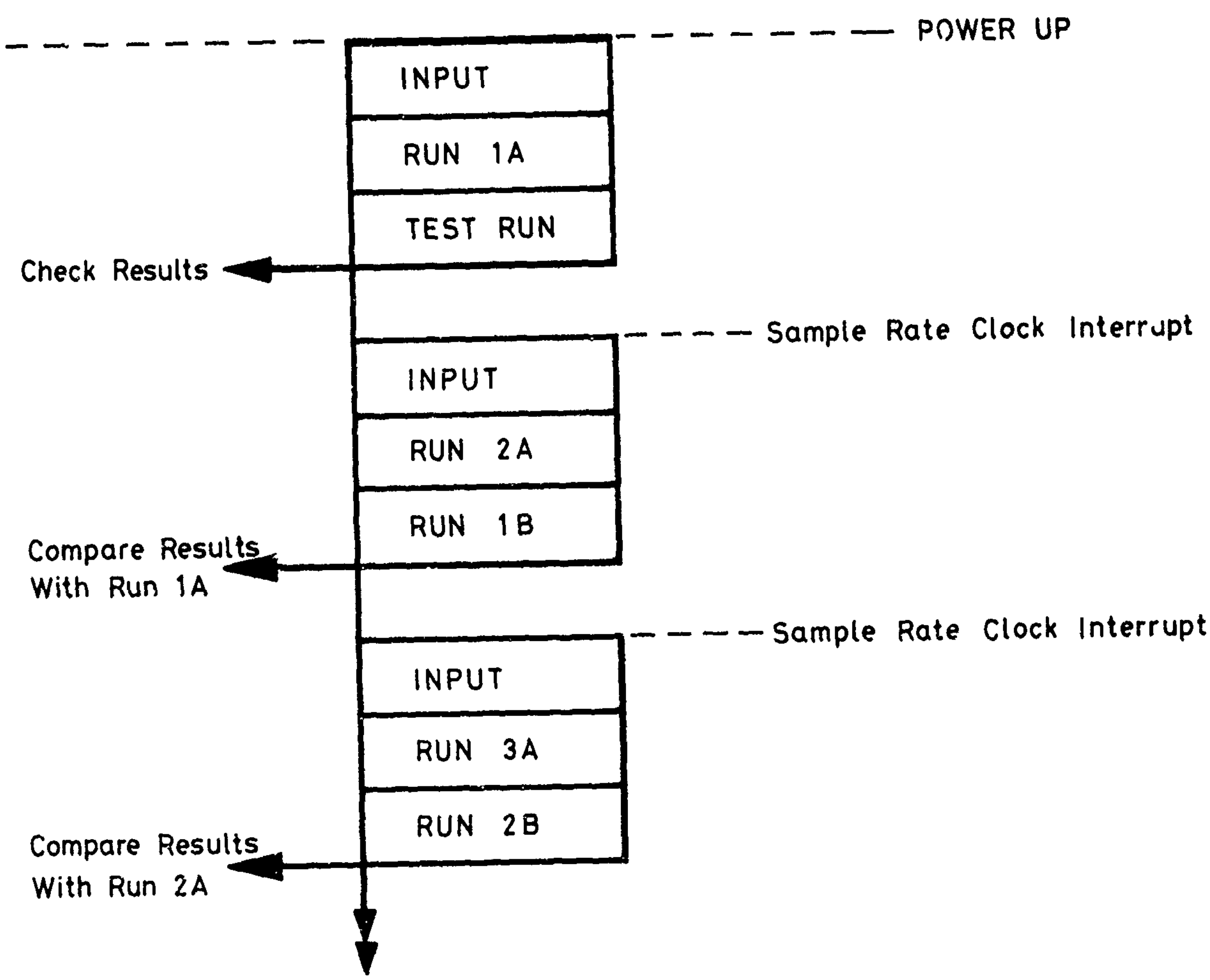

Fig.6 Processor arithmetic monitoring procedure

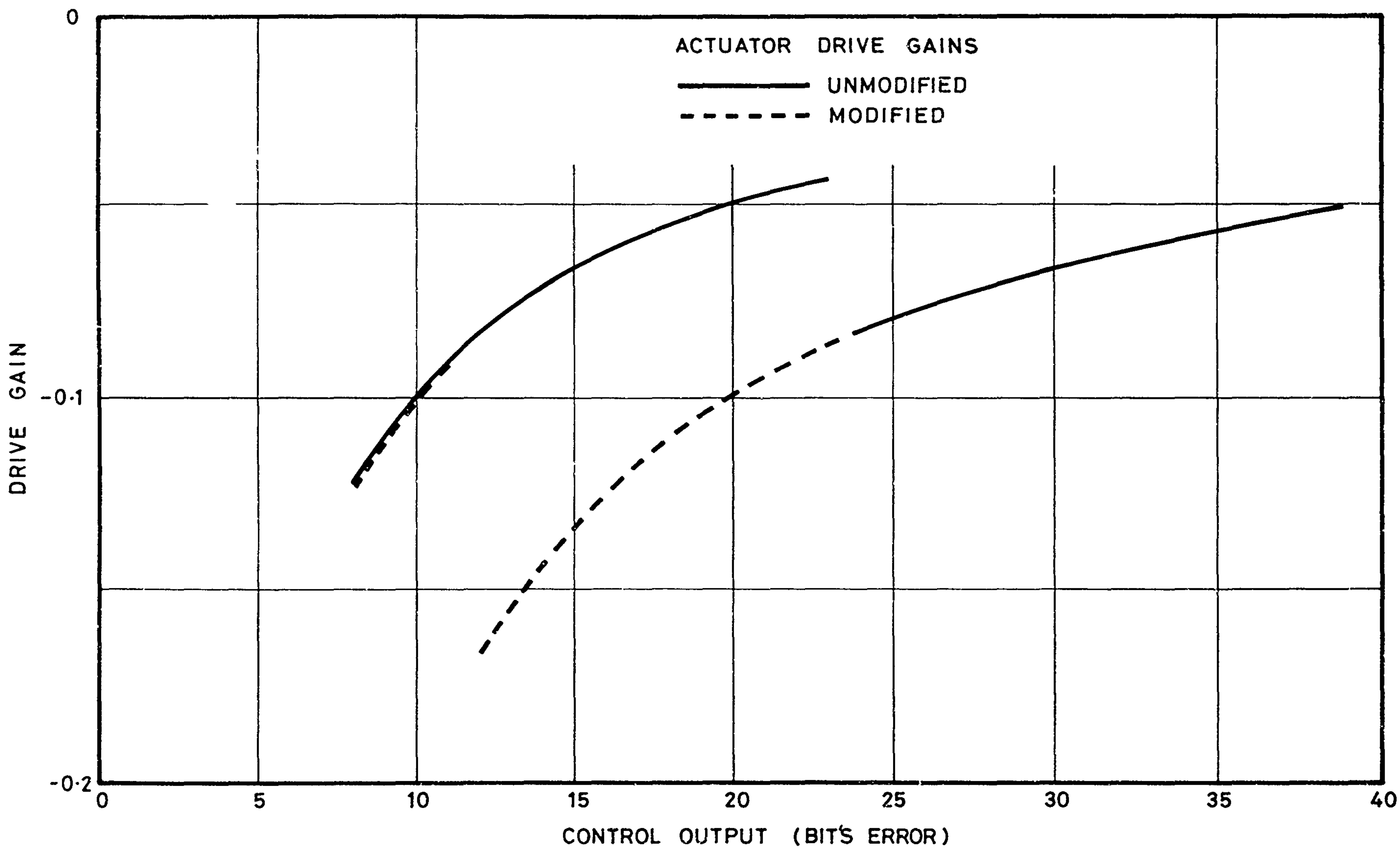

Fig.7 Output gain

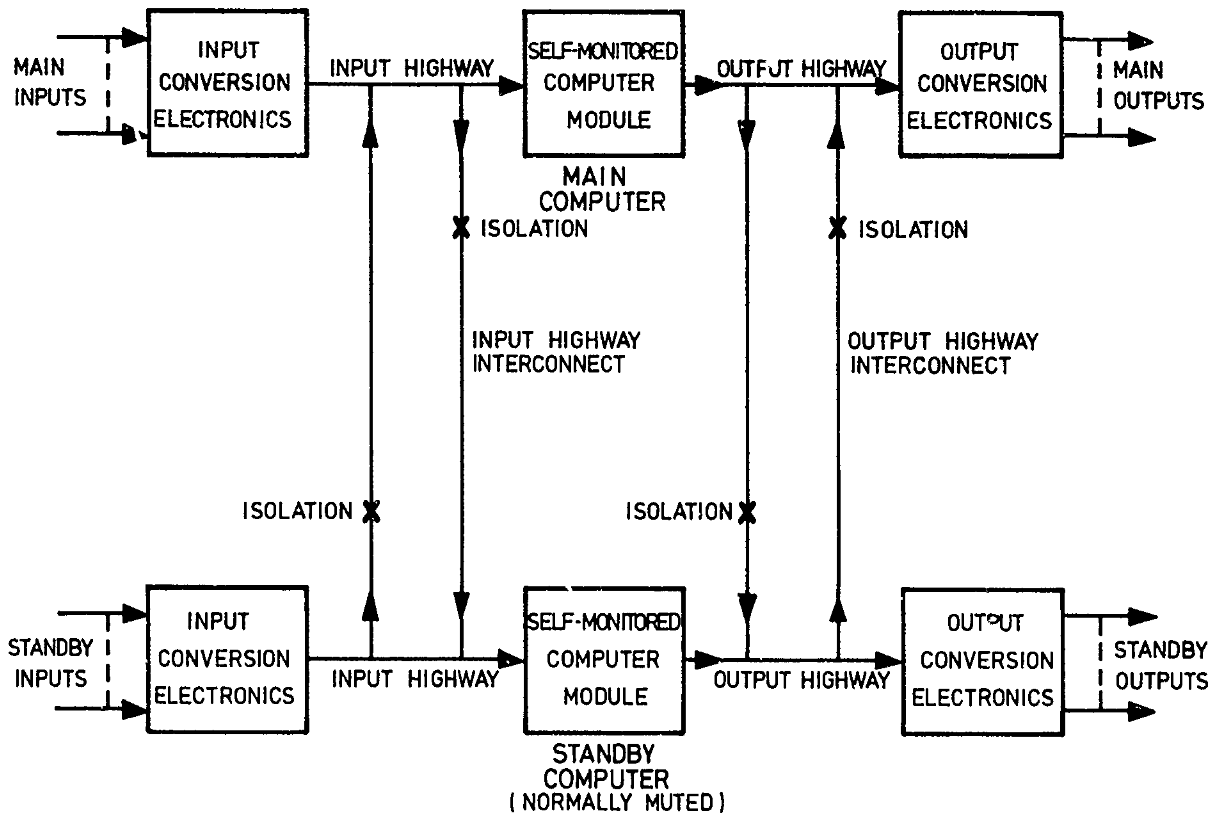

Fig.8 Interconnected digital system

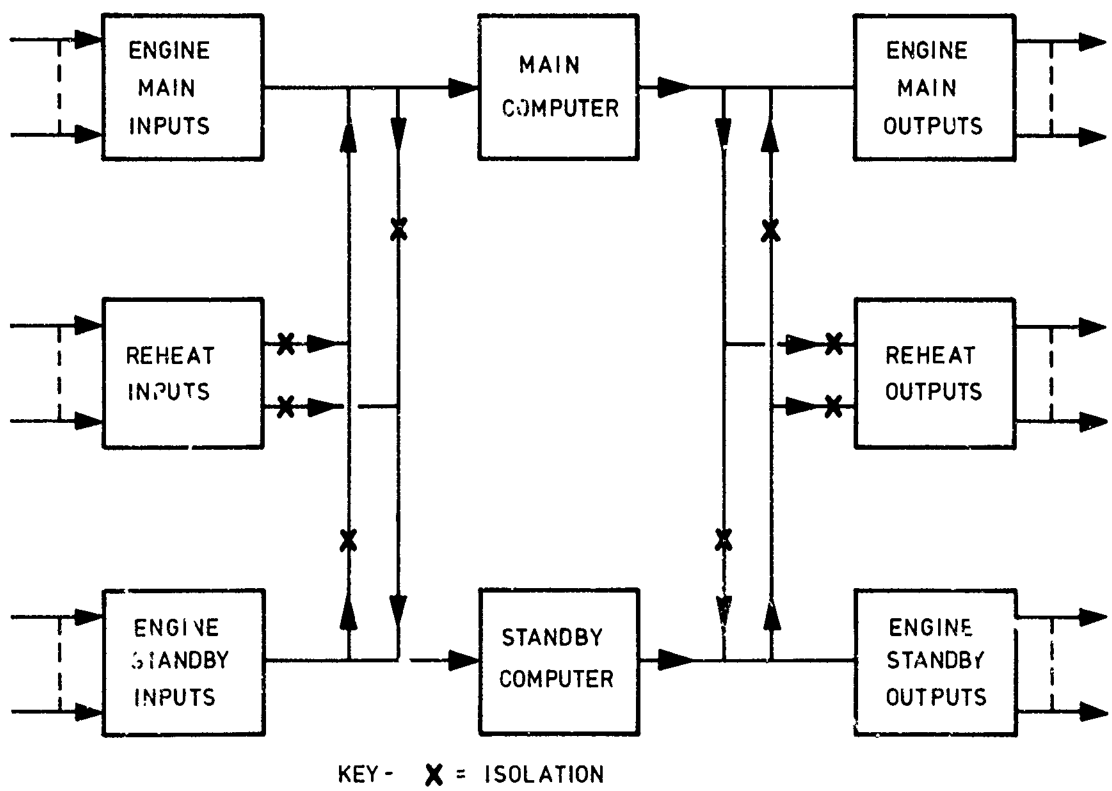

Fig.9 Simplex reheat in interconnected system

DISCUSSION

R.Cocking, UK

Could you please comment on the reliability of the software?

Author's Reply

In this type of system there must be no software errors. This can only be achieved by

1. a very high standard of documentation,
2. thorough testing at all levels, and
3. no means of permanently altering the program with no record.

The program was written and tested early in 1976 and we have yet to find a fault. Several thousands of hours of testing have taken place, a considerable time using the control unit as a development tool both in aircraft and on the test bed.

R.Cocking, UK

Could you comment on the fault integration technique compared with "freeze on third consecutive fault" used by W.T.Mitchell on the space shuttle.

Author's Reply

The fault integrator was specifically designed to provide the exact change-over response under lane failure conditions as its analogue counterpart, e.g. the automatically changeover occurred 1.5 seconds after detection of a permanent fault.

I believe that in using an up-down counter arrangement as in the Concorde System, it provided a more graceful degradation of the system. In the SSME control using Liquid Hydrogen/Oxygen the demarcation between operating and the need to shutdown is very critical. Thus should a device "strike" 3 consecutive times it will be declared failed and permanently disqualified, e.g. 60 milliseconds.

A.A.Martino, US

Describe what parameters you measured to determine what you noted as "Engine Life Recording"

Authors Reply

The engine life recorder was based on the Pegasus engine and is concerned mainly with recording stress in the engine components which tend to limit time between overhauls. The programming effort in the Concorde control system concentrated on producing a program capable of recording cycle damage, whether it be for speed or temperature cycles and creep life.

Thus the life recorder program indicating speed cycle fatigue and creep life occupied 450 words and an execution time of 500 μ sec.

Parameters were N_H and T_J available in the control.

J.Peikert, Ge

(1) Controller Mounting. Engine mounted or A/C mounted?

(2) Environmental Testing. Extremes of temperature, vibration and EMC testing, with especial interest in HF-susceptibility. What are the max field strength in v/m, to which the controller has been tested?

Author's Reply

(1) Airframe mounted – in a 1/2 ATR long case.

(2) Test extremes are:

$$\left.\begin{array}{ll}\text{Upper temperature} & +\ 70°\text{C} \\ \text{Lower temperature} & -\ 40°\text{C}\end{array}\right\}\ \text{Operational}$$

Normal acceleration level was 8.25 g (5.5 g factored by 1.5) in 3 planes each at 1 minute minimum.

Survival acceleration 10 g for 1 minute.

Radio interference test complied to SB/8/07-5001-01* Test 27, iss 1 for susceptibility and suppression

Transient voltage test in accordance with SB/8D/5010-01* App.A, Amend.4 or SB/8/07-5001 01* Test 29 iss.1

Field strengths of 10 V/m

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* BAe SST Specification

THE SECONDARY POWER SYSTEM CONTROL UNIT, AN ELECTRONIC SUBSYSTEM IN THE PANAVIA TORNADO

by
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ABSTRACT

The TORNADO is equipped with two accessory drive gearboxes which operate hydraulic pumps, fuel back-up pumps and electric generators.

The gearboxes are driven either by the APU via the APU-clutch or by the aircraft engines. A second clutch, the CD-clutch, allows the mechanical connection of both gearboxes.

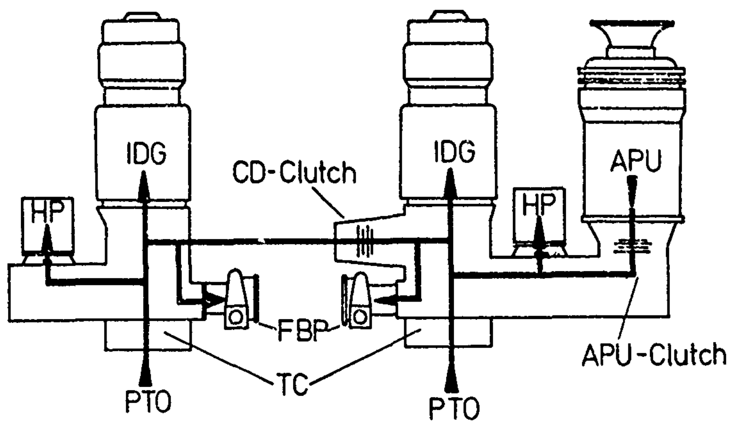
The automatic starting cycle of the APU, operation of the accessory drive gearboxes under well defined speed- and acceleration conditions and the starting phase of the aircraft engines are controlled and monitored by the Secondary Power System Control Unit, an electronic subsystem.

If a failure occurs during system operation the control unit opens the corresponding clutch or shuts down the APU, stores and displays the type of failure on LED indicators and actuates the master alarm on the maintenance panel.

The control unit is equipped with built-in test features for all internal protection circuits and for external sensors and transducers.

1. INTRODUCTION

In order to fully understand the operation of the Secondary Power System Control Unit - abbreviated SPSCU - we must first take a close look at the Secondary Power System itself.



APU	Auxiliary Power Unit
IDG	Integrated Drive Generator
HP	Hydraulic Pump
FBP	Fuel Backing Pump
TC	Torque Converter with Freewheel
PTO	Power Take Off

Fig. 1

The Secondary Power System

The PANAVIA TORNADO Aircraft is equipped with two Gearboxes (GB) which are driven by the two Main Engines. Both Gearboxes primarily fulfill the same task and are nearly identical in construction.
Each Gearbox in turn drives an Integrated Drive Generator (IDG), a Hydraulic Pump and a Fuel Backing Pump, thus supplying the TORNADO AIRCRAFT via the Secondary Power System with electrical and hydraulic power.

Additionally, both Gearboxes can be driven by an Auxiliary Power Unit (APU) which ensures the full function of the Secondary Power System on the ground even with the Main Engines shut down.
The APU is first started by means of the Aircraft Battery and accelerated to nominal speed. After the APU has reached its rated RPM the APU-Clutch engages thereby accelerating the R/H Gearbox to rated speed. Once on speed the R/H Gearbox can accelerate and drive the L/H Gearbox by means of the CROSS-DRIVE-CLUTCH (CD-Clutch). In this way the Secondary Power System can be operated stationary by the Auxiliary Power Unit.

When starting a Main Engine the Torque Converter in the corresponding Gearbox is filled with oil and the engine accelerates. As soon as either engine has reached 60 % of its rated RPM the APU is automatically shut down and the APU-Clutch opens. The Gearbox is then driven by the Main Engine.

Normally, during flight each Main Engine drives its own Gearbox. However in case of an inflight shut down of a Main Engine the corresponding Gearbox can be automatically connected to the remaining engine by means of the CD-Clutch. This guarantees the redundancy of both Gearboxes.

All Control Functions, Regulating and Monitoring Functions necessary for starting and operating the APU, for accelerating and operating both Gearboxes are accomplished in the Secondary Power System Control Unit.

2. SECONDARY POWER SYSTEM CONTROL UNIT

The SPSCU is a Line Replaceable Unit which - due to its different functions - can be subdivided into an APU-Section and a GB-Section.

2.1 APU-SECTION

The APU-Section, which is called APU-Control Unit (APUCU), controls the automatic starting cycle of the APU. This cycle is initiated by pressing the Starter Button in the Cockpit.
During start up, acceleration, and after successfully attaining rated APU RPM the APUCU monitors the normal APU operation and controls the following external devices:

Air Inlet Door
External Fuel Cock
Master Fuel Valve
Starter Solenoid
Ignition Fuel Valve
Ignition Unit
APU Start Counter
APU Operating Hours Counter
APU Operating Light (Cockpit) and
Master Alarm (Maintenance Panel)

In addition to the above, the APUCU also monitors the following APU signals:

Air Inlet Door open
External Fuel Cock open
APU RPM
Starter Temperature and
Low Oil Pressure

Should one of the signals being monitored by the APUCU behave abnormally or should it be unable to reach its nominal value within an exactly defined time period the APU is automatically shut down and a stored Fault Light is illuminated on the front plate of the Control Unit.

The most important of the signals being monitored by the APUCU is the APU RPM signal. It is sensed by an Inductive RPM Transmitter.

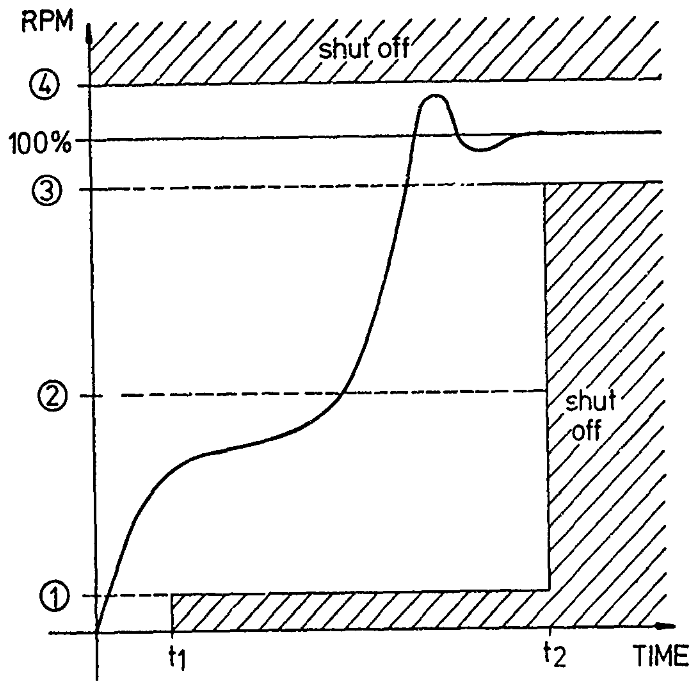


Fig. 2
APU Speed Signal Monitoring

The Starter can only be engaged if the transmitter does not sense a RPM signal; in other words the APU must be at a standstill.
However, should the sensed RPM frequency be insufficient after Starter engagement (t1) then the starting cycle is automatically aborted as the danger of a mechanical Turbine Problem or a defect RPM Transmitter might exist.

As soon as the RPM exceeds the second Threshold Value the Starter, the Ignition System and the Ignition Fuel Valve are switched off and the APU accelerates by its own. An electronic interlock prevents reengaging the Starter in case of a momentary RPM loss after Starter disengagement. A very precise Time Monitoring Circuitry ensures that the APU is immediately shut down if the necessary RPM for disengaging the Starter is not attained within a certain time period (t2).

A third RPM Threshold is set shortly below Rated RPM. When the RPM reaches this Threshold the Lubrication Oil Pressure is monitored and a signal for closing the APU-Clutch is generated.

A decrease in RPM below the Threshold or exceeding the time measurement t2 shuts the APU down because of a possible overload condition.

A fourth RPM Threshold protects the APU against destruction by rapidly shutting it down at Overspeed.

During Starter operation the Starter temperature is sensed. If the temperature rises above a permissable value the Starter is automatically disengaged and cannot be reengaged until cooled down to a safe temperature. In this case the APU will not be shut down and all monitoring circuits will stay active. This ensures the normal completion of the Starting Cycle if sufficient RPM has been attained prior to Starter disengagement. However, if the APU has not yet reached enough speed to accelerate by its own at the moment of Starter disengagement then any of the afore mentioned Time Monitoring Circuits will shut the APU down before a damage might occur.

2.2 GB-SECTION

The GB-Section (GBCU) of the SPSCU primarily controls and regulates the function of the APU-Clutch and the CD-Clutch. Both clutches are hydraulically operated.
The following input signals are processed in order to fulfill this task:

- Oil Temperature R/H Gearbox
- Oil Temperature L/H Gearbox
- RPM R/H Gearbox
- RPM L/H Gearbox
- APU-Clutch Pressure
- CD-Clutch Pressure

In addition, the GBCU processes the following discrete Aircraft command signals:

CD-AUTO/DISENGAGE
CD-RESET
Speed Switch R/H Engine
Speed Switch L/H Engine

The main responsibility of the GBCU is to regulate the APU-Clutch or the CD-Clutch precisely in such a way as to accelerate the corresponding Gearbox to rated RPM at the maximum permissable rate. This is accomplished by employing the oiltemperature prevailing at that moment as it is very important to protect the delicate IDG's against exceeding the maximum allowable temperature-dependent acceleration envelope.

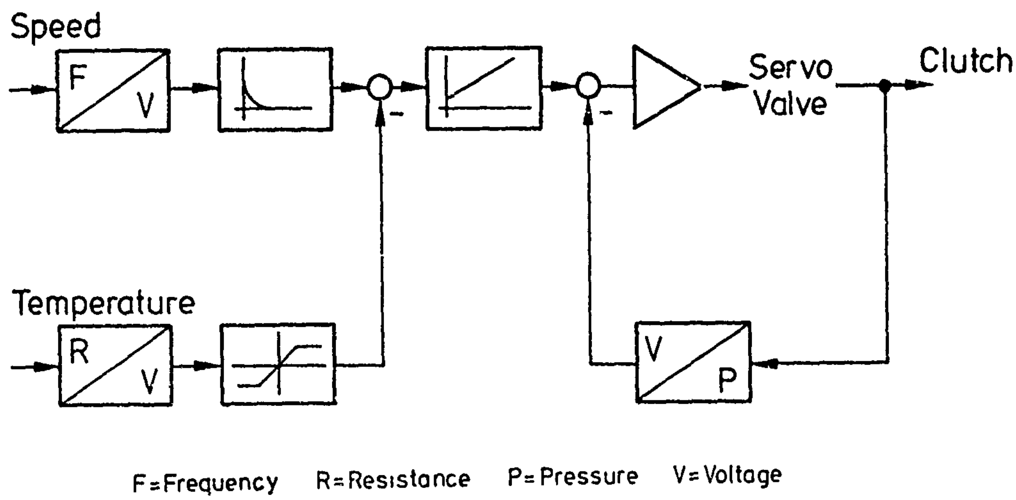


Fig. 3

Clutch regulating Diagram

The Regulating Circuit Diagram shown above is identical for both the APU-Clutch and the CD-Clutch. When regulating the APU-Clutch the GBCU processes the input signals RPM and temperature of the R/H Gearbox while the resulting output signal operates the Servovalve thereby regulating the clutch operation. When regulating the CD-Clutch the GBCU always processes the lower RPM Signal and the lower Oiltemperature Signal of the two gearboxes. The inductively generated RPM Signal is differentiated to represent the Actual Acceleration Value.

The temperature value, which is sensed by a PTC-Resistor, determines the Acceleration Set Value according to a predetermined Characteristic Curve. Subtraction of the Actual Acceleration Value and the Set Acceleration Value generates an error signal which is processed in a PI-Controller. The resulting output signal operates the Servo-valve which in turn operates the corresponding clutch.

In order to improve the regulating capability a Clutch Hydraulic Pressure Signal is fed back into the regulating circuit.

There are several different operating modes for both clutches. The APU-Clutch and the CD-Clutch can both be operated in the Modes "OPEN", "CONTROLLED" and "FIX CLOSED", while the CD-Clutch can be additionally operated in the "OPEN INTERLOCKED" mode.

Normally, the APU-Clutch is "open" below Rated APU RPM. However, as soon as the APU reaches Rated RPM the operating mode shifts to "controlled", thereby accelerating the R/H Gearbox at maximum permissable rate. When Gearbox RPM and APU RPM are equal the clutch enters the operating mode "fix closed" and hence provides the rigid connection APU-R/H Gearbox while the APU is running.

The CD-Clutch stays "open" as long as the pilot leaves the CD-Switch in the "open" position.
As the switch is placed to the "CD-AUTO" position, the clutch automatically shifts to the operating mode "controlled" when the difference in RPM of both Gearboxes exceeds a certain value and when at least one of the two Gearboxes operates at a certain minimum RPM. This operating mode is true for example if a steady state Gearbox is automatically started while the other Gearbox is already on speed or if a Main Engine is shut down during flight. Thus, the regulated operation of the CD-Clutch enables the automatic RPM equalization of both Gearboxes within permissable limits.
As both Gearbox RPM's are equalized the CD-Clutch automatically shifts to the operating mode "fix closed".

In case, however, that the slower running Gearbox does not reach a certain minimum acceleration value within 2,5 secs after beginning of the automatic regulating cycle the operating mode "open interlocked" is automatically engaged. Simultaneously, the fault signal "OVERLOAD" is generated in the GBCU, which results in the Illumination of the corresponding fault light and triggers the MASTER ALARM.

3. DESIGN FEATURES

3.1 MECHANICAL CONSTRUCTION

The cast Aluminum Housing of the SPSCU is attached to the Airframe via four shockmounts.

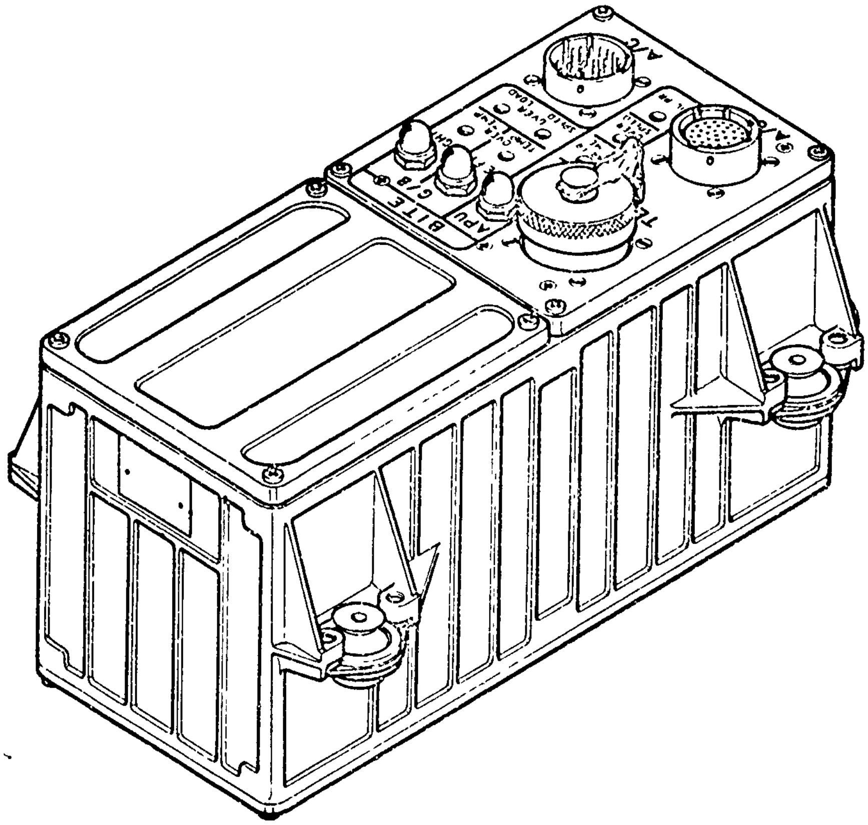


Fig. 4

The Secondary Power System Control Unit

One section of the Housing contains the 9 Printed Circuit Boards with all logic circuits while the other section houses a plug-in type Chassis which carries the Power Supply, the Power Relays and the Interface Circuit. All external electrical connectors and all control elements are attached to the Frontplate of the Chassis.

All 9 Printed Circuit Eoards as well as the Chassis are plug-in type Modules which can be easily replaced - without the need for special tools - after a cover has been removed. The electrical connection between the Printed Circuit Boards and the electrical components attached to the Chassis is accomplished by employing a Multi-Connector Plate with the associated interconnecting wiring. This Plate, which is easily replaceable due to its modular construction, is mounted in the lower part of the Housing.

All subassemblies of the SPSCU can be replaced without the need for a special post adjustment or post calibration.
The SPSCU is hooked-up to the airplane via two electrical connectors which are attached at the Front Plate of the plug-in type Chassis.

3.2 ELECTROMAGNETIC COMPATIBILITY

In order to improve the EMC-Capability of the SPSCU a subdivision into a Power-Connector and a Signal-Connector was mandatory. All electric wiring which is closely associated with the 28 V Power System of the aircraft is fed into the Power-Connector, while all wiring which has to conduct delicate signals and which is therefore shielded, is fed into the Signal-Connector.

The strict separation of the Signal-Wiring and the Power Wiring is continued inside the SPSCU. In the vicinity of the Power-Connector a special Chamber had to be installed. This Chamber is very carefully shielded and houses the Power Relays for controlling several external devices. All electrical connections between the components housed in this Chamber and all other components in the SPSCU are consequently run via EMC-Filters. Thus, the employment of the technique just described above and the additional careful bonding of all components provide the SPSCU with a very high EMC-Capability. This EMC-Capability, which is required according to PANAVIA Specs. 90001 and 90003 has been successfully proved during previous Qualification Tests.

3.3 TESTABILITY

A third electrical connector, which is also attached to the Front Plate and which is normally protected by a cap, is used for test purposes. This Test-Connector, which has 128 pins, enables the technican to perform the complete Acceptance Test or a Fault Diagnosis down to Module Level without opening the SPSCU.

Even with the SPSCU still mounted to the airframe the Secondary Power System can be tested with a Special Test Set via the Test-Connector, and, if necessary, a Fault Diagnosis may also be accomplished. In addition 3 Push-Buttons are mounted on the Front Plate. The Push-Buttons operate the BITE-System, which is divided into an APU-Section, and a GB Right and a GB Left Section. The BITE-System monitors the dormant protection circuits of the SPSCU. The results of the BITE-Tests are displayed on the Front-Plate by 8 LED's. Any faults occurring during the operation of the Secondary Power System will also be displayed by these LED's.

In addition, the OR-Connection of each of the 8 possible Fault-Signals triggers the Master-Alarm at the Maintenance Panel. However during BITE-Testing the Master alarm in the SPSCU is suppressed.

3.4 THE ALGORITHMIC STATE MACHINE

The most important functional task for the APUCU and the GBCU is to digitally control and monitor the different operating modes in which both systems are engaged at that moment.
For example the APUCU can assume the Internal States

INITIAL STATE I
INITIAL STATE II
STARTING I
STARTING II
RUN UP
APU RUNNING and
STOP

Each one of the above mentioned Internal States is processed in conjunction with the APU RPM, the corresponding Parameters and the Internal Time Monitoring Logic. Also in each one of these Internal States certain characteristics of the Input Signals are being monitored and Special Command Signals for actuating external components are generated (for example the commands "Engage Starter" or "Close Master Fuel Valve" etc.). The change-over from one State to the next can only take place at exactly defined Time Schedule with the corresponding Input Signals assuming exactly defined conditions.

The GBCU controls the CD-Clutch in a similar manner. Here, the following, already previously mentioned States may be assumed:

OPEN
CONTROLLED
FIX CLOSED
OPEN INTERLOCKED

The circuit arrangement technique employed for both, the APUCU and the GBCU is called "Algorithmic State Machine".

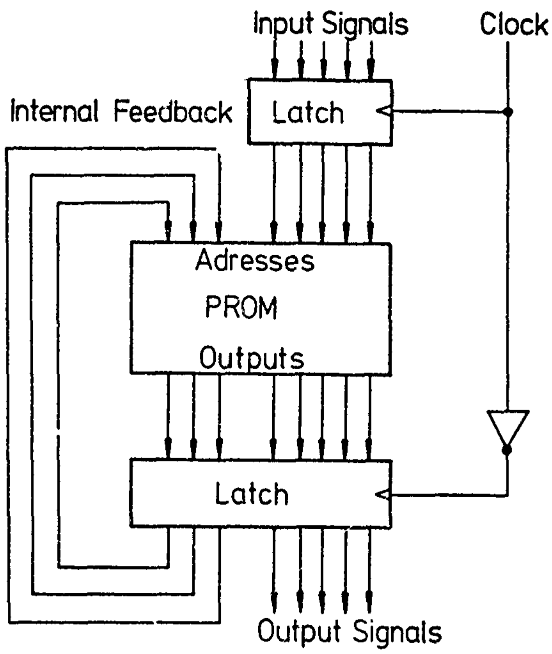


Fig. 5

The Algorithmic State Machine

This means that all Input Signals being monitored are stored with a repetition frequency of approximately 30 Hz at the rising slope of each Clock Pulse. Thus, the signals gathered in conjuntion with a feedback operate a Programmable Read Only Memory (PROM), whereby the Address Code represents the System State valid at that moment.

The multiude of all possible 2^n Addresses at n addressbits resembles the total of all operating modes. Due to the specific program design the PROM Output Signals deliver intelligent data for all possible operating modes, i.e. which State should be adopted next and which decisions should be made with regards to the controlled output variables.

With the falling slope of the Clock Pulse this data is transferred to a second memory where it is stored for further usage.
Due to this special design of the Logic the circuitry which determines the response of the APUCU and the GBCU is very flexible programmable and - because of its slowly clocked function - very resistant against undesired noise.

As the system reponse can be programmed separately for each operating mode it is readily possible to recognize - by employing the proper Software - any unrealistic combination of Input Signals (for instance as in case of a fault, etc.).
It is also readily possible to initiate the corresponding countermeasures and/or generate the proper Fault Signal. Thus, an additional opportunity for monitoring the internal unit function is provided.

3.5 POWER CONSUMPTION

During the SPSCU design state the attention was focused on low power cosumption. The Application of the CMOS-Technique was therefore adopted whenever possible. The PROM's however operate with such unfavourable Power Consumption factors that the benefit of the rest of the circuitry would have been nullified. So, in this case, a special circuit design was necessary to compensate for the disadvantage mentioned above.
This was accomplished in the following way:

Due to the Clocked function of the Sequential Logic a PROM Information Signal is generated each 30 msecs, however the actual Signal Read-Out Time is much shorter, namely less than 2 µsec.

Since a PROM does not lose its memory during a power shut down and since all output data is immediately stored after it has been read, it is possible to switch off the power supply to the PROM's during the relatively long time intervals between each read-out. This action does in no way change the response of the Logic, but the Power Consumption will be improved by the factor 15 x 10^3 compared to PROM's being continuously under power. Thus, the benefits of the CMOS-Technique could be fully enjoyed.

The RPM Monitoring of the APU and the Time Monitoring of the APUCU and the GBCU are also accomplished digitally. In this case presettable Down-Counters are loaded by the PROM's.

They determine all Times and RPM's with quartz-based accuracy. The advantage of programming very flexible and of reducing the Power Consumption by switching off the Power Supply to the PROM's between each Read-Out interval is in this case also successfully utilized.

4. CONCLUSIONS

Finally, it should be mentioned that the SPSCU can be easily tested and maintained without major difficulties thanks to the special efforts taken during the development phase to the unit.
At this moment the following items are in the design stage or under construction or have already been supplied to the customer:

A tester for the entire Secondary Power System for field use,
a Special to Type Test Equipment for the SPSCU and
the ATLAS Software for Testing and Trouble Shooting with Automatic Test Equipment.

Also during the design stage, special attention was paid to the very high demands for environmental compatibility like Temperature, Altitude, Vibration, Shock, Acoustical Noise, EMC, Contamination, etc. This was verified by the relatively unproblematic execution of the Type Approval Tests.

Since January 1978 the SPSCU is in series production for the Weapon System PANAVIA TORNADO.

DISCUSSION

G.E.Davies, UK

How much power in watts do you save by switching the PROM power supplies?

Author's Reply

Your question can be answered in two steps

(1) The APU and Gearbox sequencing circuitry contains two PROMs, each pulling approximately 140 milliamperes from the 28 Volt supply through a series regulator. Continuous PROM operation would result in approximately 7.8 Watts power consumption. With the duty-cycle 2 μs/30 ms the consumption decreases to approximately 0.5 Milliwatts!

(2) The speed and time measurement circuitry of the APU Control Unit operates two PROM's which would consume another 7.8 Watts, if not switched off.

During APU start-up three time measurements are taken. This means that one of these two PROMs is switched on for a total of approximately 6 Microseconds and then stays switched off for the remaining time of system operation. This saves additional 3.9 Watts.

The power for the APU speed measurement PROM is clocked (under worst-case-condition, which is "APU at maximum speed") with a duty-cycle of 2 μs/142μs. This results in an actual consumption average of 0.5 Watts and a saving of approximately 3.4 Watts.

In total the average saving in power consumption for the whole Control Unit due to clocked power for the PROM's is approximately 15 Watts.

CONCURRENT DEVELOPMENT AND TEST OF A DIGITAL ELECTRONIC CONTROLLER WITH AN ADVANCED VARIABLE CYCLE ENGINE

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SUMMARY

The need for high performance propulsion systems with wide operating envelopes has resulted in the design of advanced technology variable cycle engines. The sophistication of this type of engine design has resulted in increasingly complex requirements for the engine control system as well as for engine components. Implementing the intricate control schemes for an advanced technology variable cycle engine can be best accomplished using a full authority digital electronic controller. The capabilities of the digital controller allow for safe and stable operation of the engine while optimizing engine performance over the flight envelope. In addition, the flexibility of the digital controller facilitates engine development testing by accommodating new engine component characterizations as they evolve and by implementing special test functions that can be controlled by the test engineer.

This paper describes a program in which a full authority digital electronic controller is used as a tool in the development of an advanced technology variable cycle engine. The concurrent development of an engine mounted digital controller and an advanced technology variable cycle engine imposes unique problems yet provides several advantages. These problems and advantages will be highlighted in the discussion of the control system development.

LIST OF SYMBOLS

DDA	--	Detroit Diesel Allison
JTDE	--	Joint Technology Demonstrator Engine
ATEGG	--	Advanced Turbine Engine Gas Generator
EH-K1	--	Model Designation for Bendix Digital Controller
A/D	--	Analog to Digital Converter
D/A	--	Digital to Analog Converter
RAM	--	Random Access Memory
ROM	--	Read Only Memory
VCE	--	Variable Cycle Engine
CPU	--	Central Processing Unit
CRT	--	Cathode Ray Tube
PROM	--	Programmable Read Only Memory
EPROM	--	Erasable Read Only Memory
PLA	--	Power Lever Angle
LVDT	--	Linear Variable Differential Transformer

INTRODUCTION

Preliminary design studies were conducted by Detroit Diesel Allison (DDA) to identify specific advanced technologies that would satisfy future Navy and Air Force weapons system propulsion requirements, and these technologies are being incorporated in the DDA Joint Technology Demonstrator Engine (JTDE).

The JTDE is a two-spool Variable Cycle Engine (VCE) incorporating the following technologies:

-- High performance, distortion tolerant fan

-- Variable flow capacity compressor

-- Staged combustors for nigh efficiency

-- Variable flow capacity high pressure turbine vanes

-- Variable flow capacity jet flap low pressure turbine vanes

-- Plug-type primary exhaust nozzle

-- Advanced materials

-- Complete actuator/sensor/digital control system

The advanced development of these technologies was supported through the DDA Advanced Turbine Engine Gas Generator (ATEGG) program with the ATEGG being a subset of the JTDE.

While the engine hardware was developed by DDA, the development of the digital electronic controller was the primary responsibility of The Bendix Corporation, Energy Controls Division. The specifications for an engine mounted digital electronic controller for the JTDE posed numerous hardware and software design challenges. The electronic controller requires the interface hardware and software to control two compressor geometry loops, two fuel loops, two turbine geometry loops and two exhaust nozzle loops. Hardware interfaces had to be designed to accurately measure engine temperatures, pressures, speeds, and actuator positions (resolvers, LVDTs and potentiometers). In addition, system safety requires that special attention must be paid to the reliability of the components used in the system to insure the proper operation of the controller in the harsh engine environment of high temperatures and high vibration levels. Other system constraints are that the engine parameter inputs must be read and the control computation completed at a high enough frequency to permit stable operation of the high response control loops, and extensive parameter monitoring and health checks be made to insure fail-safe shutdown in the event of any out-of-tolerance condition.

To facilitate the concurrent development with an advanced technology variable cycle engine, maintainability was a key design parameter in the electronic controller's hardware and software. The controller hardware was partitioned into functional modules to aid in quick fault isolation and module replacement. Similarly, the software was partitioned into functional modules to aid in software verification and to allow for rapid accommodation of new engine component characterizations. Another consideration was to include provisions for enhancing the testability of the system software and hardware to aid in debugging problems which arise during the software verification and engine testing.

A block diagram of the JTDE/electronic controller is shown in Figure 1. The goals of the controller program described in this paper were two-fold: improved engine performance through the use of the electronic controller on the JTDE and the development of an electronic controller system that will be ready for production with the engine. The remainder of the paper summarizes the program developments in the control mode, hardware and software design of the electronic controller.

CONTROL MODE DEVELOPMENT

The development of an electronic controller concurrently with an advanced technology variable cycle engine draws together an engine design program and control feasibility studies. With the use of the digital controller, the engine designers were able to take advantage of closed loop control of engine geometries and accurate steady-state governing of the engine which was previously run manually. The control designers gained experience in applying control laws to advanced, working hardware.

Control feasibility work proceeded in parallel with the ATEGG engine development and test program. As engine test data became available, it was incorporated into the digital simulation models at DDA. These models were used to solve the multiloop control problems presented by a variable cycle engine with the resultant loop interactions. DDA performed trade studies to determine which engine parameter could be most effectively controlled by each control variable. Trade studies were also made to achieve a balance between the engine operational requirements and safe operation in terms of steady-state and transient margins from surge, as well as mechanical and thermal limits. From these preliminary studies emerged a definition of the control laws to be applied to the engine. Compromises were made in the control mode as hardware and technological constraints were defined or became known. All minor (actuator position) loops are closed through the digital controller in addition to the major (engine parameter) loops. These minor loops presented some unique problems in that some devices being controlled were existing laboratory hardware which in some cases were not well sized for digital control loops. In these loops, the dynamics of the digital computer become significant and limit the realizable bandpass of the servos.

Once the minor loops had been sized, it was then possible to resize the gains in the major loops for the given control laws. This was done on the ATEGG with classical techniques and linear descriptions of the engine. First, the fuel flow loop was closed and designed to a desired set of stability margins. Then the geometry loops were sized to specific stability margins considering the fuel loop as a closed inner loop. When the loops were sized and their linear performance known, nonlinear transients were again simulated at DDA and performance verified. Figure 2 shows a block diagram of the fuel control mode, and Figure 3 shows a typical actuator position loop.

In order to verify correct operation of the electronic controller prior to engine tests, a real time nonlinear engine model was programmed on the Bendix hybrid computer with simulated sensors and actuators added to the model. When the software coding was finished and had been checked in an open loop, the controller was moved to the hybrid computer and used to close the simulated loops as shown in Figure 4. The closed loop system is then tested to insure that the simulated system provides the expected frequency response and transient results.

The flexibility of the digital control has been evident in a demonstration program of this type. As the ATEGG has gone through succeeding tests, the control mode has evolved from the original concepts. These modifications were accomplished by software changes. Prior to each engine test, the software updates are incorporated and checked in a closed loop with the simulation for correct operation.

As the program progressed to the JTDE phase, a similar control law development process occurred. Because of the complexity of the JTDE, the loop sizing process was performed by means of extensive nonlinear digital simulation work at DDA. New control laws were then programmed in the electronic control by Bendix, and nonlinear hybrid simulation of this system was also programmed on the hybrid computer and used for software verification.

HARDWARE DEVELOPMENT

The digital electronic controller for the JTDE was designed and built using the technology available in 1975. A 16 bit Bendix microprocessor (BDX-920) was used in the electronic controller to implement the sophisticated control mode of the JTDE. Adaptability was incorporated into the unit by designing the controller hardware to interface with the ATEGG as well as the JTDE. To facilitate software changes during the engine development cycle, a 16000 word reprogrammable core memory unit external to the controller housing was used. Provisions were included in the controller housing for the final PROM/RAM or EPROM/RAM memory cards.

One of the main tasks of the electronic controller hardware is to make accurate and reliable measurements of the engine parameters (temperature, pressure, position and speed) at a sufficient update rate for stable digital control. Accurate engine temperature measurements are made by the controller by using voltage amplification circuits with cold junction compensation on thermocouple inputs. The pressure transducers are based on vibrating quartz crystals with on-board temperature compensation. Either potentiometers, LVDTs, or resolvers are used for position feedback measurements and magnetic pickups are used to supply frequency signals to the speed processing circuits. The EH-K1 electronic controller hardware incorporates the following features:

-- CONTROL MODES -- CAPABLE OF CONTROLLING DDA JTDE VARIABLE CYCLE ENGINE:

10	Modulated Torque Motor Drivers
5	Solenoid/Relay Drivers
3	Fault Indication Flag Drivers
12	Resolver Inputs
6	Thermocouple Inputs
8	Pressure Inputs
4	Speed Inputs
16	Discrete Inputs
2	Serial Digital Input Channels
1	Serial Digital Output Channel
18	Analog Input Buffers
3	Trim Potentiometers

-- LOW POWER SCHOTTKY T^2L DIGITAL LOGIC FOR CPU

-- FAULT ACCOMMODATION

-- INTERNAL POWER REGULATORS MODULES AVAILABLE FOR ENGINE ALTERNATOR, 115 V 400 HZ SINGLE PHASE OR 35 VDC POWER SOURCE

In addition to the requirement for high accuracy in the engine parameter monitoring, the electronic package design must maintain the electrical components within allowable temperature and vibration levels in order to obtain the high reliability required of the electronic controller. The electrical components are mounted on copper heat rail grids that help to dissipate the heat generated by the components with additional cooling accomplished by circulating engine fuel through the outer walls of the controller. Special care was given to the mounting of the pressure transducer subassemblies to guard against exciting the vibrating element at its resonance. Additional vibration isolation of the controller is provided through the use of shock absorbing engine mounts on the controller. The heat rail grids also provide extra stiffness to the circuit modules to minimize board vibrations.

Figure 5 shows the backplane side of the EH-K1 with the circuit modules removed. Figure 6 shows the circuit modules mounted in the controller and Figure 7 shows the EH-K1 controller mounted on the ATEGG for testing.

The interfacing of the electronic controller with the engine occurs in three phases. Initially, the electronic control is connected to the actuators with the engine shutdown for open loop tests. Loop stability and step response data is taken to insure safe and stable actuator control. During the second phase, the electronic control is running "piggyback" on the engine. At this phase, the engine running is accomplished from a manual test console. The electronic control is monitoring "live" engine parameters, but the actuator commands and feedbacks are closed through an analog loop closure box which simulates the engine actuators. The third phase is the actual control of the engine with the electronic controller. Figure 1 is also indicative of the engine test set up.

Many advantages accrue in hardware design because of the parallel development of the electronic controller and the JTDE. Obviously, the experience gained through engine testing identifies any problems in accuracy or reliability resulting in improvements that can be incorporated in the present design or in subsequent projects. This applies to both the electronic controller internal hardware and the electro-pneumatic or electro-hydraulic engine actuators. Other, not so obvious, advantages are afforded to the engine development by the electronic control. Extra margins of safety in the engine operation are possible with the electronic control because of the extensive parameter monitoring capabilities for out-of-tolerance inputs, programmed limiters to guard against exceeding temperature, pressure, or rotational limits during transients, and fail-safe switchovers from the electronic control to a backup unit of a critical failure has been detected. In addition, the repeatability of data is enhanced through the use of the electronic controller when compared with manual control. Accurate steady-state governing of the engine can be maintained while the effects of excursions of individual engine actuators are investigated. Precise, repeatable acceleration and deceleration rates can be implemented also.

SOFTWARE DEVELOPMENT

The software implementation of the control mode for the JTDE and ATEGG was written in the Bendix BDX-900 series assembly language. The software is based on structured programming with the control code divided into functional modules which implement selected parts of the entire control. In addition, numerous macro definitions were programmed for repetitive algebraic and logic sequences used in the control mode. The modular implementation of the control code and supporting code greatly facilitated the initial coding effort, the debugging effort and also subsequent control code updating of the software.

The software in conjunction with the peripheral hardware and interfaces, perform the following functions:

- -- Control mode computation in accordance with the control mode specified.
- -- Input and output processing including reasonableness checks, redundant sensor switching, and parameter synthesis.
- -- Diagnostic checks of reference voltages, I/O interfaces, CPU and memory.
- -- Real time interactive capabilities including operator control of engine geometry actuators and monitoring/modification of selected control variables.

The control software is designed to run in a real time environment with the priority requirement being the control of the engine. Two interrupts are implemented in the system as shown in Figure 8: a power-up interrupt and an interval timer interrupt. The control software structure is comprised of modules falling into four functional areas:

- Executive - Interrupt Level Response
    - -- Maintains real time reference of control solution in conjunction with the hardware interval timer
    - -- Services synchronous functions: A/D inputs, D/A outputs
    - -- Initializes operation in response to power-up interrupt caused by system power-up or a mode select switch
- Executive Monitor
    - -- Invokes the control computation at the beginning of each 20 millisecond solution interval
    - -- Schedules execution of background tasks in the time remaining after control computation
- Control Tasks
    - -- Processes inputs
    - -- Performs computations required for cortrolling fuel flows, compressor geometries, turbine geometries and nozzle areas
    - -- Detects faults and takes appropriate actions
    - -- Computes outputs to be plotted and synthesis parameters
- Background Tasks
    - -- Invokes the interactive module that allows real time monitoring and modification of selected input or outputs
    - -- Invokes software diagnostics: CPU check, memory checksum, and RAM check

One of the strengths of implementing a digital electronic control is the ability to incorporate special features in the software to aid in control mode verification as well as engine development. Also included are provisions for rapidly incorporating new data into the controller software. The following list of special purpose software modules is included as an example of the types of functions implemented in the electronic control software to enhance the engine/control system development.

MIACT	-	Interactive parameter monitor and modifier module. Allows RAM values for system variables, inputs, outputs and intermediate rates to be monitored and modified from the CRT.
MBOLD	-	Background Bendix On Line Debugger. Allows for real time modification of any core memory location from the CRT.
MIHIS	-	Histogram module. Provides for statistical data gathering of system variables.
MXYPL	-	X-Y Plot Module. Calculates output value for real time plotting of system variables.
MRAMP	-	Ramp module. Allows system variables to be ramped up or down with a selectable increment until the desired limit is reached.
MSA	-	Sine Wave Addition Module. Provides the capability to add an external signal to a system variable for frequency response testing.
MXFER	-	Transfer module. Allows the electronic control to assume engine control from the backup unit for engine start up or at engine idle.
MPLAC	-	PLA cycle module for cyclic endurance. Allows for a prescribed number of engine accel and decel cycles to be run with the accel rate, time at max speed, decel rate, and time at min. speed adjustable by the programmer/engineer/test operator.

The digital capabilities of the electronic controller also allow for extensive health checks of the control system to insure safe engine operation. Redundant inputs, as well as rate and range checks on all engine parameter inputs are used to insure the health of the input signals. Critical internal hardware circuits of the electronic controller are monitored by the software to insure the health of the controller hardware, and checks of the RAM, ROM and CPU are performed to insure the health of the CPU. All failure flags in the software are polled in the control software to determine the health of the system. If a critical failure is determined to have occurred, actions are initiated by the controller for a fail safe switchover to a manual backup controller to protect the engine from possible damage. The number of health checks performed as well as the speed at which they are checked provides a larger margin of safety to the engine than afforded by a manual "panic" button.

CONCLUSIONS

The use of a flight worthy digital controller early in the development cycle of a Variable Cycle Engine gives benefits both in the flexibility of the engine test schedule and in evolving a digital controller which will be ready for production with the engine. The techniques and experiences gained in the concurrent development provides a maturing of the state-of-the-art for both hardware and software needed for the high performance propulsion control systems of the 80's.

In order to meet the increasingly more stringent goals of the development of a VCE, new technologies are presently being developed at Bendix. A lighter flight worthy digital controller in a dual configuration implemented with a single chip 16-bit microprocessor is being developed. New quartz capacitive pressure transducer modules have also been designed which overcome previous transducer problems. New technologies are also being developed for implementing modern multivariable control laws for solving the engine control problem and for incorporating Low Cycle Fatigue calculations in the electronic controller.

The concurrent development of the digital controller and the Variable Cycle Engine will result in the realization of the goals for an advanced propulsion systems of improved engine performance, stability, hot section life and fuel economy. It will also result in an increase in the control system reliability while reducing system weight, initial cost and maintenance cost.

ACKNOWLEDGEMENTS

The work for this development program was performed in cooperation with Detroit Diesel Allison, a Division of General Motors. The authors wish to thank Mr. D. E. Warner from DDA for the information supplied for this paper with regards to the JTDE and the control mode development. We wish to also acknowledge The Bendix Corporation and Bendix colleagues for their support in publishing this paper.

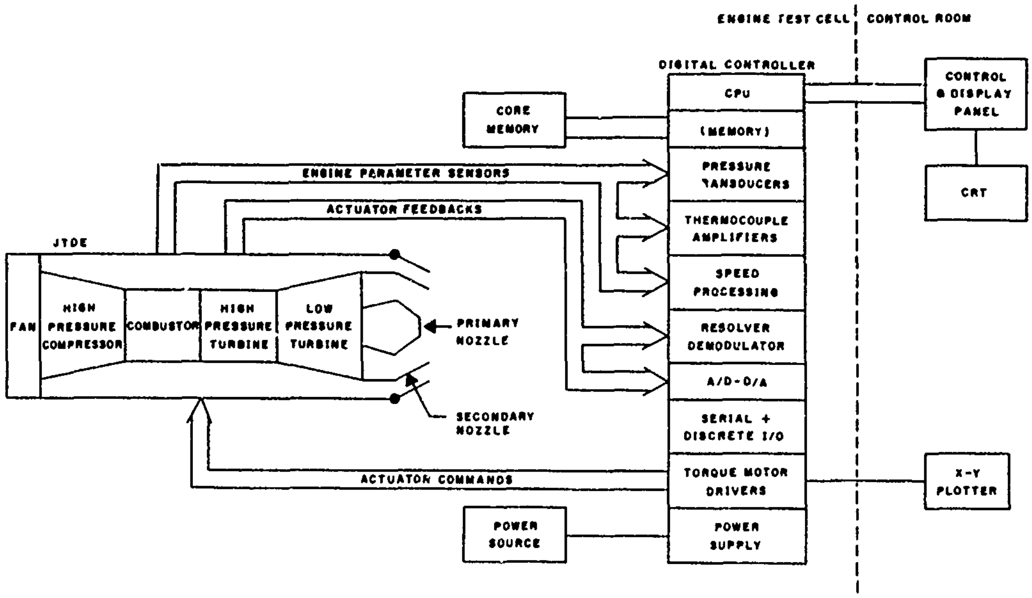

FIGURE 1. JTDE/ELECTRONIC CONTROLLER BLOCK DIAGRAM

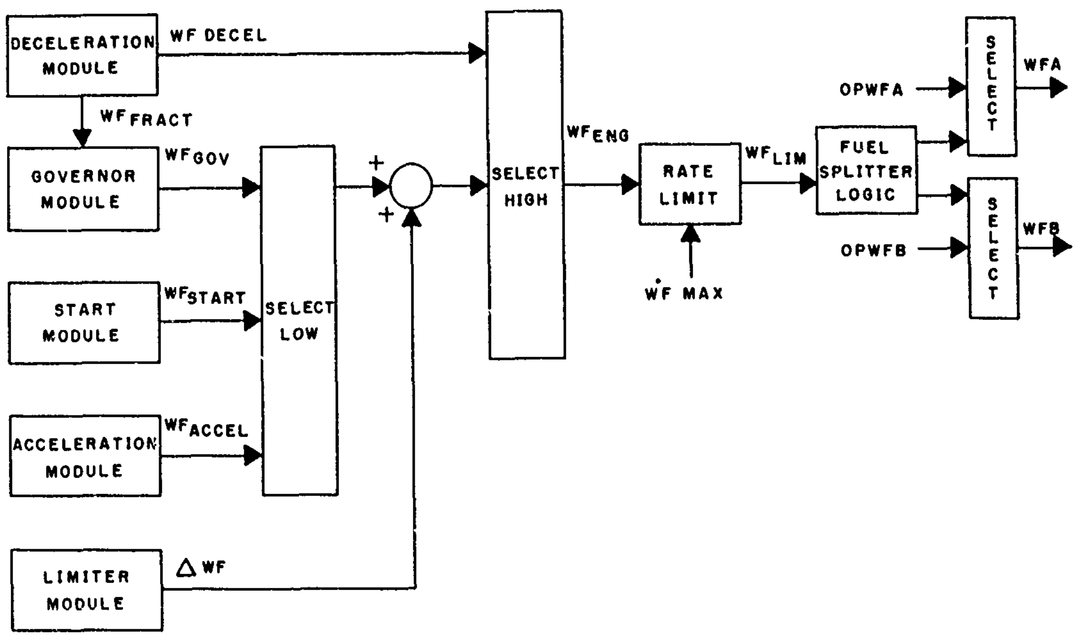

FIGURE 2. JTDE FUEL CONTROL MODE

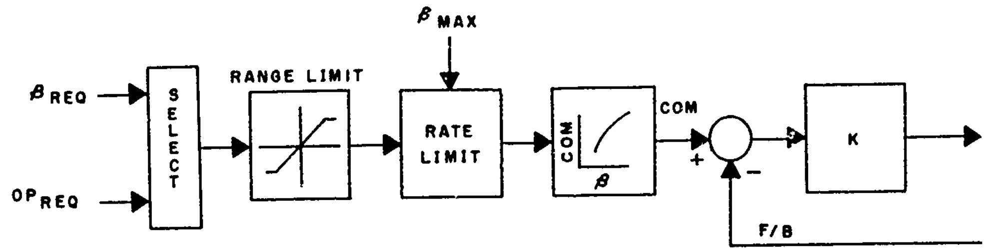

FIGURE 3. TYPICAL JTDE ACTUATOR LOOP

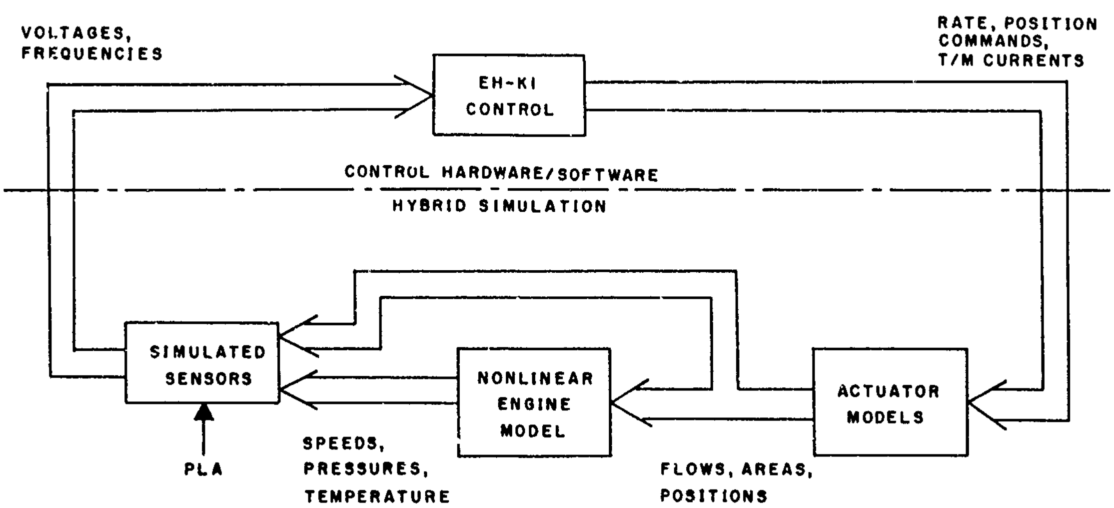

FIGURE 4. CONTROL SOFTWARE VALIDATION WITH HYBRID SIMULATION

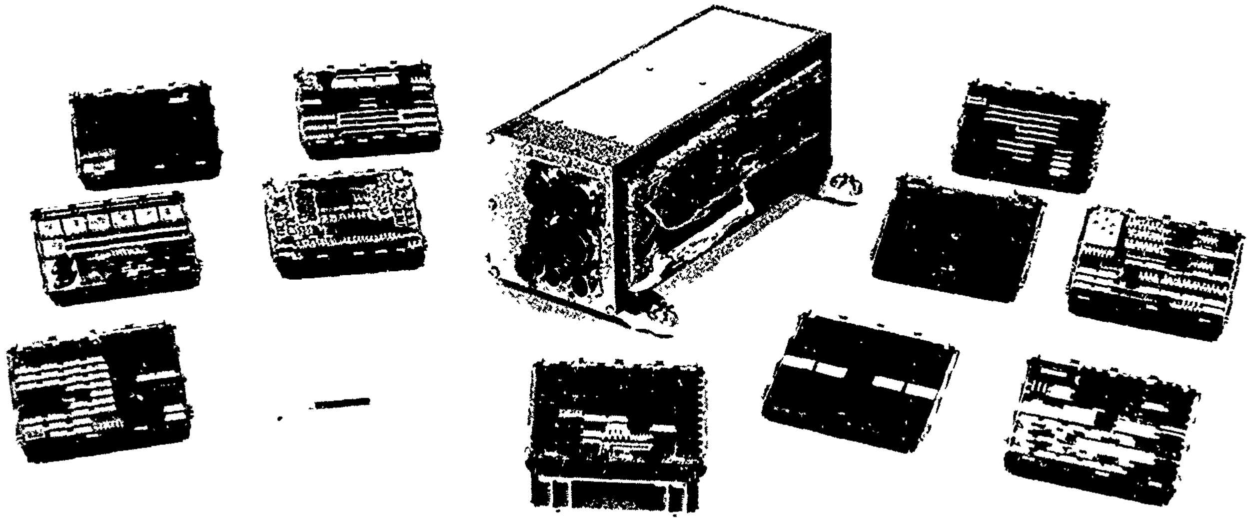

FIGURE 5. ELECTRONIC CONTROLLER WITH CIRCUIT MODULES REMOVED

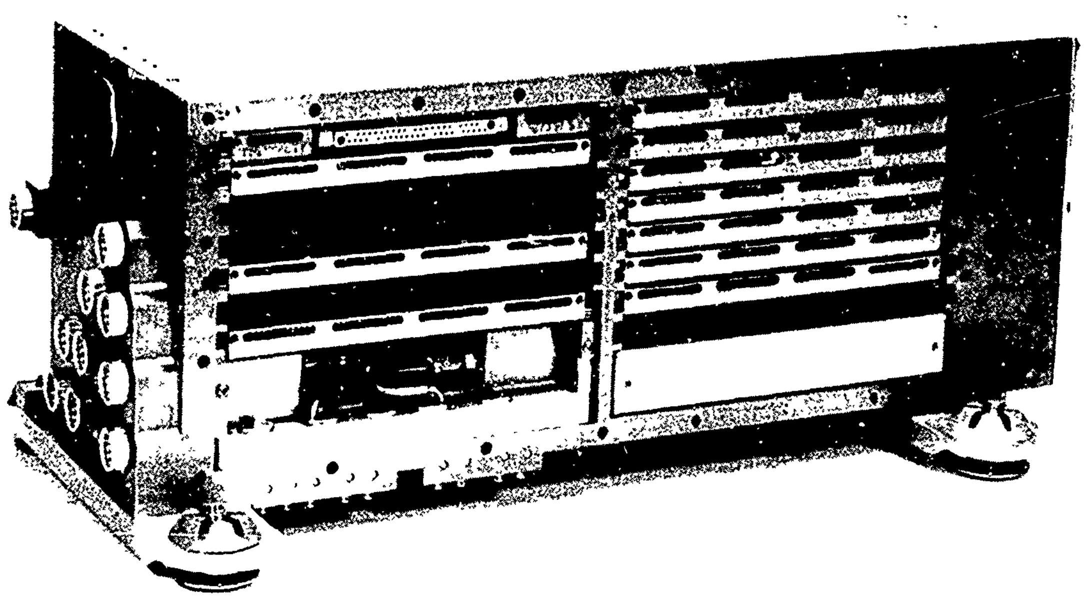

FIGURE 6. ELECTRONIC CONTROLLER WITH CIRCUIT MODULES INSTALLED

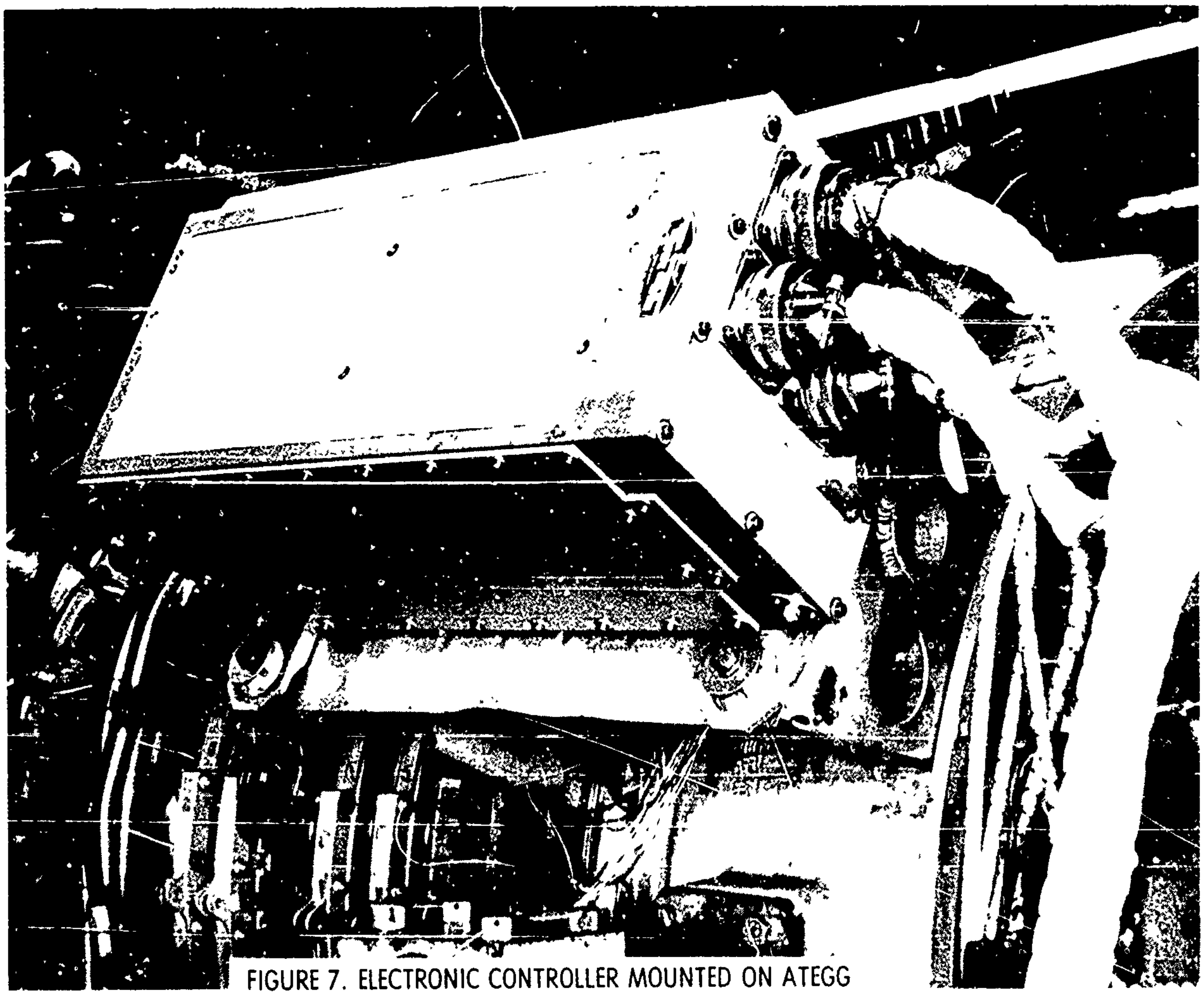

FIGURE 7. ELECTRONIC CONTROLLER MOUNTED ON ATEGG

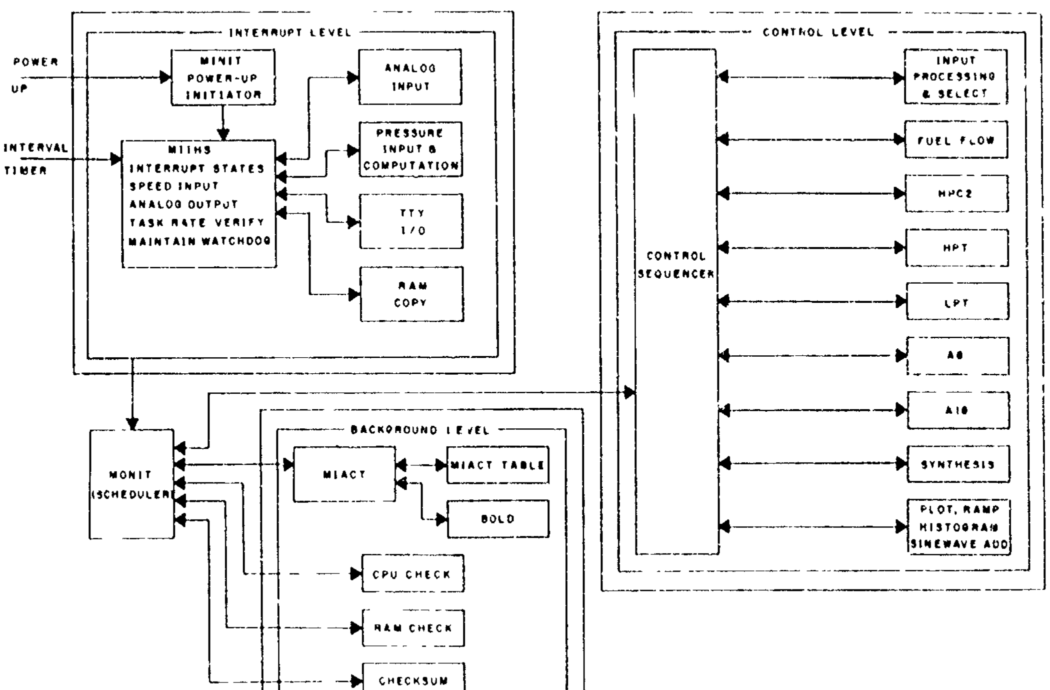

FIGURE 8. ELECTRONIC CONTROLLER SOFTWARE STRUCTURE

DISCUSSION

J.Dunham, UK

What is your back-up system?

Author's Reply

For the JTDE, which is a development engine being tested, the backup unit is simply a mechanical handvalve test fixture to bring the engine back to idle speed if a switchover from the electronic controller has occurred. This system is not for production but used only for the testing program.

B.J.Cocking, UK

Could you tell me how many sensors would be interfaced to a production unit, and how this number affects the MTBF of the unit.

Author's Reply

The electronic controller was designed to interface both the ATEGG and JTDE as well as additional growth possibilities. Thus it has provisions for approximately 50–60 inputs. The new projects that are working on have approximately 20 inputs in a dual redundant mode and we are trying to achieve 8000 hrs MTBF.

J.Legg, UK

Are quartz sensors still requiring individual calibration cards?

Author's Reply

Yes. In the pressure transducer system used for this program, each transducer has its temperature calibration data programmed into its own prom card. If you change a pressure transducer element, you must also change the associated calibration prom.

M.J.Joby, UK

(1) One of the most difficult gas turbine parameters to measure is pressure Could you indicate the accuracies of measurement set as design targets, and whether you achieved these?

(2) Over what temperature range was this achieved?

Author's Reply

(1) As I indicated in the paper, the pressure measurement is made by using a vibrating quartz crystal whose period is modulated by the pressure I believe the design target accuracy was 0.5% of point. We came close to this target by being between 8 to .5% of point.

(2) The module is bench tested from 50°C to 100°C and retains this accuracy. For engine testing of the JTDE, the environment has not approached these temperature extremes. One thing that we have tried to look at is the long term drift of this type of transducer over time and we are developing a quartz capacative transducer that will not be subject to this long term drift.

D.Schmidt, Ge

You mentioned in your conclusions that you are developing new technologies for the introduction of modern multivariable control theories to solve the engine's control problems. Of course this question if of theoretical and academic interest But which practical improvements do you expect from this development?

Author's Reply

We are just beginning to look at the use of modern multi-variable control theory and at this point I don't have any practical experience that would indicate the advantages that may occur

S.R.Tyler, UK

Could the authors please give information on positional accuracy of the nozzle position transducers and the temperature at which they are required to operate.

Author's Reply

The nozzle position transducers are simply high temperature potentiometers Since these potentiometers were existing hardware at Detroit Diesel Allison, and specified by them, I do not have the figures for the temperature range that they are designed for

NOUVEAU SYSTEME DE COMMANDE DE DEBIT DE CARBURANT POUR PETITES TURBOMACHINES

par
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RESUME

Les petites turbomachines utilisées comme systèmes de démarrage ou groupes autonomes de puissance nécessitent des dispositifs spécifiques de commande de débit carburant. Après avoir rappelé les contraintes qui leur sont propres et les différentes solutions possibles, on donne le principe et le fonctionnement d'un système original. Celui-ci est constitué d'une électropompe, dont on fait varier la vitesse par un dispositif électronique et d'un régulateur simplifié de pression différentielle. Les principaux problèmes rencontrés au cours de la mise au point de deux applications particulières sont décrits ensuite.

1. PRESENTATION

Le système de contrôle de carburant qui va vous être présenté a été développé par la Société MICROTURBO pour résoudre les problèmes spécifiques de ses petites turbomachines. Celles-ci ont des puissances thermiques sur arbre de l'ordre de 400 kW et sont utilisées en tant que :
- systèmes de démarrage
- groupes autonomes de puissance (G.A.P.)
- réacteurs

Nous ne parlerons pas ici des réacteurs, car ceux produits par MICROTURBO, étant du type simple corps, simple flux et tuyère fixe, ne présentent pas de difficultés particulières pour leur régulation. Ce système a fait l'objet d'un brevet. Avant de décrire le principe, le fonctionnement et les problèmes particuliers rencontrés au cours de la mise au point, nous vous présenterons brièvement :
- les particularités des petites turbomachines
- les principaux systèmes de contrôle de carburant utilisables
- les motifs qui nous ont conduit au développement du nouveau système

2. PARTICULARITES DES PETITES TURBOMACHINES

Pour fournir une puissance de quelques centaines de kilowatts, il suffit d'un débit d'air de quelques kilo/seconde et de vitesses de rotation de l'ordre de 50 000 tr/mn. Le faible débit et la grande vitesse conduisent à des compresseurs et turbines de faible diamètre (quelques centimètres), et par conséquent, à des inerties mécaniques très petites. Ces machines ont donc des temps de réponse très courts et des taux d'accélération extrêmement importants. Il n'est pas rare, en fonctionnement normal, d'accepter des accélérations de l'ordre de 10 000 à 20 000 tr/mn/s, et on comprend alors la nécessité d'une régulation très rapide et précise.

Pour l'avionneur, un système de démarrage ou un G.A.P. sont des équipements presque mineurs, et il faut donc réduire au maximum leur masse, leur encombrement et leur coût. Le nombre des fonctions de contrôle et de sécurité n'est pas proportionnel à la taille de la turbomachine et est pratiquement le même pour une "petite" ou une "grosse" turbomachine. Plus la turbomachine devient petite, plus la part relative de ses propres "équipements", en ce qui concerne la masse, l'encombrement et le prix, devient importante. On est donc conduit à rechercher un système de contrôle comportant un nombre minimal d'éléments simples, fiables et performants. Pour fixer les idées, nous allons vous indiquer les paramètres principaux de deux groupes typiques.

Tout d'abord, un système de démarrage qui fournit, sur son arbre de sortie, une puissance mécanique de 150 CV à 6 600 tr/mn entre - 45°C et + 45°C. La puissance massique de sortie est de l'ordre de 5 CV/kg, la puissance thermique interne étant de l'ordre de 250 kW. Ce groupe a une puissance de sortie 3 fois plus grande, à masse égale, qu'un groupe similaire développé il y a une quinzaine d'années. Il doit être capable de passer de la vitesse nulle à sa vitesse nominale en quelques secondes.

Le second exemple est celui d'un G.A.P. qui fonctionne entre - 40°C et ISA + 30°C, jusqu'à une altitude de 9 000 m, en fournissant une puissance mécanique de 200 CV et un débit d'air de prélèvement de 0,5 kg/s. Il a une puissance thermique interne de l'ordre de 450 kW pour une masse totale du caisson de 80 kg.

Il est bien évident que les spécifications de ces deux systèmes diffèrent du fait de leur utilisation Pour le système de démarrage, par exemple, on ne considère pas comme prépondérante sa consommation spécifique puisqu'il ne fonctionne que quelques dizaines de secondes. Sa vitesse de rotation n'a pas besoin d'être régulée avec une grande précision, mais par contre, on lui demande de démarrer sûrement quelles que soient les conditions de température, et d'amener le plus vite possible le réacteur à son régime de ralenti Comme il ne sert que peu de temps, sa masse et son encombrement doivent être réduits au strict nécessaire. Le G.A.P., quant à lui, devra avoir une consommation spécifique réduite, être capable de fonctionner dans une large enveloppe et, comme il entraîne le plus souvent des alternateurs, avoir une régulation de vitesse précise.

Quel que soit le type de petite turbomachine, le système de régulation de carburant qui la commande doit assurer le contrôle des trois phases principales de fonctionnement :
- l'allumage
- l'accélération
- le régime nominal

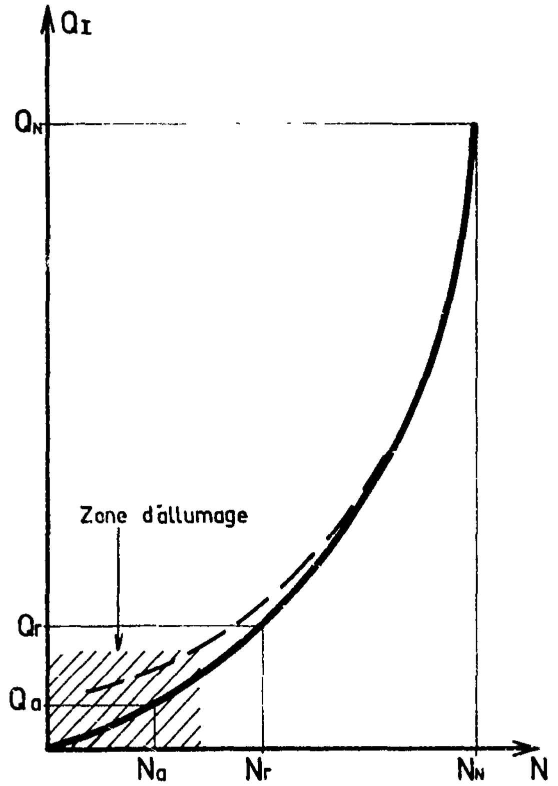


Figure 1 : Courbe Q_I = f (N)

Sur la figure 1, ci-contre, on a représenté, en traits pleins, la quantité de carburant à injecter, <u>en régime établi</u>, en fonction de la vitesse.

Bien entendu, dans la réalité, il n'y a pas une courbe unique, mais un faisceau de courbes, car la consommation varie, pour un même régime de rotation, entre autres, en fonction de la température de l'air ambiant et en fonction de la charge de la machine.

La courbe en trait pointillé représente la quantité de carburant qu'il faut injecter pour <u>accélérer</u>. Le premier point critique est la détermination de la zone d'allumage. Il faut en effet réaliser celui-ci le plus vite possible pour deux raisons :

- si on allume à vitesse élevée la flamme a tendance à être "soufflée" à l'extérieur
- si on allume tardivement, tout le carburant qui a été injecté depuis le début de la séquence s'enflamme brutalement et on obtient en général une sortie de la flamme et une extinction

On est donc conduit à avoir, au point d'allumage un débit faible. Or la technologie des injecteurs est telle que pour les faibles débits, l'angle de pulvérisation n'est convenable que si :

- le débit d'entrée est grand dans le cas d'injecteurs à prélèvement
- la pression est grande dans le cas d'injecteurs directs

Le deuxième point délicat est la détermination de la "marge" d'accélération, c'est-à-dire de la quantité supplémentaire, par rapport au régime établi, qu'il faut injecter pour accélérer. Si elle est trop faible la machine ne diverge pas ou le démarrage est trop long et si elle est trop forte, on peut avoir soit une extinction par excès de richesse, soit même un pompage si l'accélération du mobile est trop grande.

3. PRINCIPAUX TYPES DE SYSTEMES DE CARBURANT

Pour définir les différents systèmes utilisables pour les petites turbomachines, il faut examiner d'abord les éléments constitutifs.

3.1. Eléments constitutifs

Un circuit de carburant quelconque comprend essentiellement les organes suivants :
- un organe générateur de débit de carburant
- un ou plusieurs organes de réglage
- un organe récepteur : la rampe d'injection

3.1.1. Organes générateurs

Il s'agit des pompes à carburant qui peuvent être :
- soit entraînées mécaniquement par la turbomachine
- soit entrainées par un moteur

Le premier type nécessite un réducteur de vitesse entre la turbomachine et la pompe et présente un inconvénient dû à son principe. En effet, pour pouvoir allumer la machine et l'accélérer, on a besoin d'un débit important à basse vitesse, ce qui conduit à un débit surabondant au régime nominal. Il faut donc, en ce point, by-passer la majorité du débit fourni.

Les pompes entraînées par un moteur électrique peuvent présenter aussi certains inconvénients surtout dans le cas d'un système de démarrage. Leur débit dépend en effet de la tension disponible à la batterie pendant le démarrage et celui-ci peut varier dans de très grandes limites, et ceci d'autant plus que la température modifie les caractéristiques de la batterie et la viscosité du carburant.

3.1.2. Organes de réglage

On peut distinguer :
- les régulateurs mécaniques dont l'exemple typique simple est le régulateur centrifuge
- les régulateurs pneumatiques
- les régulateurs "électro-hydrauliques" tels que les servovalves

On sait que les régulateurs mécaniques et hydromécaniques ont été utilisés pendant de nombreuses années. Leur principe est, en général simple, mais leur réalisation et leur réglage sont souvent délicats, ce qui conduit à un prix de revient souvent prohibitif.

Les servovalves ont fait l'objet, pendant de nombreuses années, d'une suspicion due à leur fragilité. Elles sont maintenant parfaitement au point, mais leur technologie conduit à des usinages très délicats, donc à des prix trop élevés et sont aussi, de ce fait, sensibles à la pollution du carburant.

3.1.3. Organes récepteurs

En ce qui concerne les petites turbomachines, on n'utilise que deux types d'injecteurs :
- les injecteurs directs
- les injecteurs "à prélèvement" ou "à retour"

Les premiers ont l'avantage d'être extrêmement simples et donc fiables et peu coûteux. Nous avons d'ailleurs utilisé, dans une application particulière, de simples injecteurs directs employés normalement dans les brûleurs de chaudière de chauffage central

Malheureusement, ce type d'injecteur n'a de bonnes qualités de pulvérisation que si le rapport entre le débit maximal et le débit minimal à injecter est de l'ordre de :

$$\frac{Q\ max}{Q\ min} < 3$$

Les injecteurs à prélèvement sont donc nécessaires dans la majorité des cas. La Société MICROTURBO a fait un important effort d'industrialisation pour produire, à des prix compétitifs, des injecteurs de ce type, ayant d'excellentes caractéristiques de pulvérisation afin de pouvoir les utiliser dans la majorité des systèmes produits actuellement.

3.2. Architecture de quelques systèmes

Nous allons présenter brièvement trois systèmes qui ont été utilisés par MICROTURBO.

3.2.1. Système "pneumatique"

Il comprend, d'amont en aval, ainsi qu'indiqué en planche 1 :

- une électropompe dont la vitesse est régulée à $\pm$ 5 % par un contacteur centrifuge incorporé au moteur
- un électrodistributeur dont l'alimentation électrique est commandée par une capsule placée dans le bloc régulateur et permet de n'injecter du carburant que lorsque une certaine pression règne dans la chambre de combustion
- un bloc de régulation dont la disposition est telle que le débit de carburant est asservi à la pression P2 régnant dans la chambre de combustion
- une rampe d'injecteurs directs spéciaux. Il s'agit en effet d'injecteurs comportant un clapet taré. Les réglages des clapets des huit injecteurs sont décalés les uns par rapport aux autres de manière à ce que, au fur et à mesure que la pression fournie par la pompe augmente un nombre grandissant d'injecteurs se mettent à pulvériser. Le principe de ce système est très simple. Il faut noter cependant que le débit étant asservi à la pression P2 régnant dans la chambre et que celle-ci varie avec la température et l'altitude, on n'obtient pas une vitesse de consigne fixe ce qui, dans l'application décrite ici et qui concerne un système de démarrage, n'a pas une importance primordiale. Les problèmes rencontrés sont d'ordre technologique : tout d'abord au niveau des injecteurs dont la fabrication et le réglage sont délicats, ensuite au niveau de la régulation centrifuge du moteur de la pompe dont les caractéristiques évoluent dans le temps.

3.2.2. Systèmes électrohydrauliques

Deux variantes ont été successivement employées, toutes deux utilisant des injecteurs à prélèvement.

3.2.2.1. Système à électropompe

Ainsi que le montre la planche 2, ce système comprend :

- une électropompe à vitesse non régulée et comportant un régulateur de pression dont le fonctionnement est associé à un régulateur de débit
- un régulateur de débit qui ne peut fonctionner seul car il ne peut pas by-passer de débit. Pour maintenir le débit dans la fourchette de réglage (de 145 à 155 l/h) il modifie la pression régnant à son entrée et celle-ci, en se répercutant sur le régulateur de pression monté en amont, permet à ce dernier de by passer le débit excédentaire
- une servovalve . Celle-ci est placée en série dans le circuit de prélèvement des injecteurs. Commandée par un boîtier électronique, elle "ouvre" ou "ferme" plus ou moins le circuit de retour au réservoir. Son circuit pilote hydraulique est pris directement sur le circuit normal étant donné que les différences de pression entre l'entrée et la sortie sont faibles.
- une rampe d'injecteurs à prélèvement

Ce système a révélé à l'usage un excellent comportement et a même permis, par de simples réglages, d'être adapté à un système de démarrage qui devait être capable de fonctionner en altitude. Il comporte malheureusement beaucoup d'éléments et certains sont fort coûteux comme, par exemple, la servovalve.

3.2.2.2. Système à pompe entraînée

Celui-ci, décrit à la planche 3, comprenait :

- une pompe entraînée, à travers un réducteur, par la machine. Pour permettre le démarrage, cette pompe fournissait, au régime nominal, un débit énorme de l'ordre de 900 l/h, sous une pression de 16 bars.

- un bloc hydraulique constitué lui-même de deux éléments :
  * une servovalve placée comme précédemment dans le circuit de prélèvement
  * un clapet différentiel ; celui-ci étant rendu nécessaire par le fait qu'il n'existe pas, sur le marché français, de petites servovalves capables de fonctionner sous une différence de pression de 16 bars.
- une rampe d'injecteurs à prélèvement. Ce système était compact, mais présentait encore des inconvénients dus à la servovalve. Celles-ci, en effet, ont un débit de fuite non nul qui peut conduire, dans certaines conditions climatiques, à des démarrages avortés par extinction pauvre. De plus, le problème du prix de revient de cet élément restait posé.

4. MOTIFS DU CHOIX DU NOUVEAU SYSTEME

L'expérience acquise en exploitation par les systèmes décrits ci-dessus avait permis de définir sûrement deux des éléments constitutifs, à savoir :
- les injecteurs à retour
- l'électropompe

L'organe régulateur ne pouvait être : ni une servovalve, car cet élément est cher et sensible à la pollution, ni un régulateur pneumatique, qui ne permet pas de contrôler avec précision la vitesse de la machine.

C'est alors qu'est née l'idée de repartir la fonction de contrôle entre deux éléments :
- l'électropompe qui, étant un élément électrique, peut être commandée par une électronique de régulation
- un clapet différentiel, qui va jouer le rôle d'un amplificateur hydraulique. Ce dernier élément peut ne pas paraître nécessaire puisque en faisant varier la tension aux bornes de l'électropompe, on fait varier le débit. Mais les caractéristiques des injecteurs à prélèvement sont telles que pour obtenir une variation substancielle du débit injecté, il faut faire varier de manière importante la perméabilité du circuit de prélèvement. Ce qui revient à dire que le gain $\Delta QE/\Delta QI$ est faible, QE étant le débit d'entrée de la rampe, et QI le débit injecté. On pourrait s'en contenter, mais cela conduirait, pour réaliser les variations de débit injecté de l'ordre de 6 à 10, que l'on rencontre communément, à demander à la pompe des variations de débit de l'ordre de 20 à 50 ce qui conduirait à une électropompe trop encombrante et trop lourde.

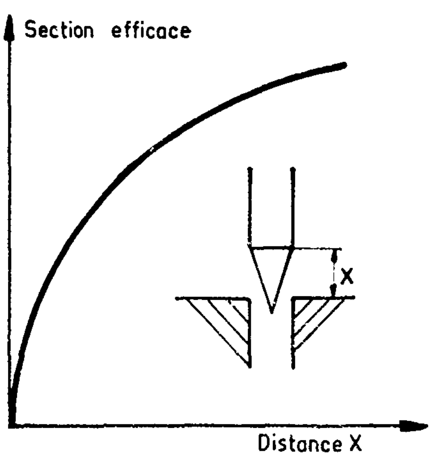
Il faut noter que dans le cas où l'on peut utiliser des injecteurs directs, on peut alors se passer du clapet différentiel, et on est conduit à un système particulièrement simple puisque ne comprenant qu'une électropompe commandée en tension et une rampe d'injecteurs.

5. PRINCIPE ET FONCTIONNEMENT DU NOUVEAU SYSTEME

Le système comporte donc :
- une partie électrique comprenant une électropompe à vitesse variable commandée par un boîtier électronique
- une partie hydraulique comprenant :
  * un clapet différentiel
  * une rampe d'injecteurs à prélèvement

5.1. Partie hydraulique

Le clapet différentiel proprement dit est constitué comme indiqué sur la planche 4. On voit qu'il est réalisé très simplement et "ouvre" ou "ferme" le circuit de retour en fonction de la différence de pression à ses "bornes". Il est branché en parallèle sur la rampe d'injection et est donc soumis à la différence de pression $P_{CE} - P_{CR}$. Tant que cette différence de pression est inférieure à l'effort du ressort, le circuit retour est ouvert et présente une perméabilité maximale. Lorsque le débit d'entrée augmente la perte de charge de la rampe d'injection augmente. Au moment où cette perte de charge devient égale à l'effort du ressort, le clapet différentiel commence à agir en fermant le circuit de retour.



Il faut remarquer ici la technologie de l'organe de réglage qui est constitué par un pointeau pénétrant dans un siège cylindrique. En effet, si l'on trace la courbe de la section efficace de passage en fonction de la distance entre les deux organes, on obtient une courbe de la forme indiquée ci-contre, qui montre que le gain du système n'est pas linéaire.

On peut tracer en laboratoire les caractéristiques de la rampe d'injection et du clapet différentiel, mais ces courbes sont d'un emploi peu pratique.

Il vaut mieux tracer les caractéristiques complètes de l'ensemble sous la forme d'une courbe $Q_I = f(Q_E)$ qui est beaucoup plus parlante.

On trouvera à la planche 5 une telle courbe et l'on remarque immédiatement la non linéarité du système :
- pour les faibles Q_E, le gain $\frac{\Delta QI}{\Delta QE}$ est faible
- pour les forts Q_E, le gain $\frac{\Delta QI}{\Delta QE}$ est grand

Contrairement à ce qu'on pourrait penser, cet aspect est favorable.

En effet, on a un gain minimum pour les QE et QI minimaux, c'est-à-dire pendant la phase délicate de l'allumage et de l'accélération, et l'on dispose des gains maximaux pour les forts débits, c'est-à-dire aux alentours de la vitesse nominale, là où, justement, il faut assurer le meilleur contrôle de la vitesse.

Il faut noter que la partie quasi horizontale de la courbe dépend essentiellement du circuit de retour. Ceci revient à dire que si les pertes de charge dues aux tuyaux, raccords, clapets... etc, sont sensibles, ou bien si le circuit de retour est pressurisé, on translate la courbe vers le haut et on arrive ainsi à avoir des débits trop grands pour assurer un allumage correct.

Comparons maintenant les courbes QI = f (QE) obtenues pour divers réglages du clapet différentiel à la courbe de consommation N = f (QI), on remarque que ces courbes ont une allure générale similaire. (planche 5)

La différence entre les deux réglages provient d'une différence entre les valeurs des différences de pression auxquelles le clapet entre en action. On remarque que dans la partie de variation de courbure, celle-ci est plus faible pour le réglage de différence de pression le plus élevé et conduira donc à une accélération plus régulière de la machine.

On a donc intérêt à choisir un réglage du clapet différentiel aussi élevé que possible aux deux conditions suivantes près :

- qu'il permette une accélération suffisante de la machine jusqu'à la moitié de la vitesse nominale
- que le plein régime de la machine soit obtenu pour des valeurs de Q_E raisonnables, c'est-à-dire ne conduisant pas à surdimensionner l'électropompe.

5.2. Partie électrique

L'interface entre la partie hydraulique et la partie électrique est assurée par l'électropompe.

5.2.1. Electropompe

Celle-ci est composée d'une classique pompe à engrenages, donc du type volumétrique, entraînée par un moteur électrique à excitation indépendante. On sait que, pour un tel moteur, si l'excitation est constante, la vitesse de rotation, et par là, le débit de carburant fourni par la pompe, est une fonction quasi linéaire de la tension qui alimente l'induit : $Q_E = f\ (Up)$.

Il faut noter dès maintenant que si en fonctionnement normal autour du point de régulation peut considérer que la tension d'excitation est constante, il en va tout autrement pendant la phase de démarrage. En effet, celui-ci est généralement réalisé par un moteur électrique puissant et ayant donc une consommation importante puisque de l'ordre de quelques centaines d'ampères. Celle-ci entraîne donc une chute de tension importante de la source et il est fréquent, en particulier lors de démarrages réalisés sur batterie, de voir la tension descendre à 60 % de la tension nominale. Ce phénomène peut être particulièrement génant puisque pendant la phase délicate du démarrage, toutes les fonctions de transfert, y compris celle de la pompe, vont évoluer.

Fort heureusement, le moteur se comporte comme un moteur shunt et sa vitesse augmente donc lorsque l'excitation diminue ce qui provoque donc une sorte "d'auto-compensation". Pour pouvoir fournir le débit maximum de 200 l/h sous une pression de 12 bars en tenant compte d'un rendement global de 0,4, il faut disposer d'un moteur d'une puissance de l'ordre de 240 Watts, soit une intensité maximale, pour une tension d'alimentation de 24 V, de l'ordre de 10 ampères.

5.2.2. Découpeur

Un courant de 10 ampères peut être actuellement facilement commandé par un transistor. Celui-ci peut être utilisé, soit en "ballast", c'est-à-dire se comporter grossièrement comme une résistance variable, soit en "découpeur", c'est-à-dire fonctionner en "tout ou rien".

La deuxième solution est la plus avantageuse au point de vue de la dissipation thermique et permet d'augmenter la sureté de fonctionnement du transistor et de diminuer la masse du radiateur chargé d'évacuer les calories. En effet, dans le fonctionnement en ballast, on est amené à dissiper dans le transistor la différence entre la puissance d'entrée, c'est-à-dire le produit de la tension batterie par le courant absorbé par le moteur, et la puissance aux bornes du moteur.

Or, comme l'on doit être capable de fonctionner même avec des tensions d'alimentation relativement basses, on est amené à choisir un moteur capable de fournir le débit maximal à la sortie de la pompe pour une tension de l'ordre de 22 à 25 Volts. On doit donc dissiper au minimum 40 Watts dans le ballast. La dissipation est encore plus élevée pendant la phase de démarrage où l'on désire des débits plus faibles. Par contre, dans le cas d'un transistor travaillant en découpeur, on ne dissipe que :

- la puissance perdue du fait de la chute de tension collecteur-émetteur pendant que le transistor est conducteur (soit $I.V_{CE}$)
- la puissance perdue par les pertes de commutation lorsque le transistor passe de l'état passant à l'état bloqué et inversement. En choisissant bien le type de transistor utilisé, on peut rendre ces pertes extrêmement faibles.

Nous utilisons des transistors Darlington de technologie Mesa triple diffusion pour lesquels on a :

- un temps de montée tr = 0,4 μs
- et un temps de descente tf = 0,9 μs

Présenté en boîtier T03 Jumbo, ce transistor à une intensité collecteur nominale de 20 ampères et une intensité de pointe de 40 ampères ; il peut dissiper 70 Watts à 125°C. Nous avons mesuré en fonctionnement normal un rendement global variant de 84 à 94 %, les plus mauvais rendements étant obtenus lorsque la tension d'alimentation tombe aux alentours de 20 Volts ce qui conduit le découpeur à être pratiquement en conduction continue. Le schéma bloc du découpeur est donné à la planche 6. Il s'agit d'un découpeur à fréquence fixe et à largeur variable. On remarque qu'il comporte une boucle de régulation interne.

A l'entrée de l'amplificateur de régulation R, on a :

- la tension de commande provenant de l'étage de régulation
- la tension "image" de la tension fournie par le transistor de puissance. Etant donné que cette tension est composée d'une suite de créneaux à fréquence fixe et à largeur variable, le contenu harmonique très riche d'un tel signal nous a obligé à réaliser un filtre actif du 2ème ordre qui fournit en sortie une tension continue fonction de la tension moyenne fournie par le découpeur à la pompe.
- la tension de "pulse au démarrage". Au cours des essais, nous avons constaté que l'on pouvait améliorer le démarrage du groupe en fournissant pendant une brève période de l'ordre de 1 à 2 secondes, la pleine tension d'alimentation à l'électropompe. Cet à-coup de tension fait démarrer très vite le moteur de l'électropompe et l'à-coup de débit qui s'en suit remplit rapidement les canalisations et force l'injecteur à pulvériser correctement dès le début de la séquence, ce qui permet de réaliser très rapidement l'allumage même par temps très froid. L'amplificateur de commande C est en réalité un comparateur qui reçoit sur l'une de ses entrées la tension de sortie de l'amplificateur R et sur l'autre le signal provenant d'un oscillateur ou plus exactement d'un générateur de rampes.

Compte-tenu de la bande passante du moteur de l'électropompe et de la turbomachine, la fréquence de découpage a été choisie relativement basse, de l'ordre de 250 Hz. En sortie, a été disposé un circuit de protection qui comporte d'une part des éléments passifs destinés à limiter les suroscillations et d'autre part un circuit actif qui bloque le transistor de puissance si les tensions d'alimentation des amplificateurs ne sont pas toutes deux présentes.

Bien entendu, un découpeur génère des harmoniques sur un très large spectre et il a fallu prendre un certain nombre de dispositions pour respecter les normes dans le domaine des interférences radioélectriques. Celles-ci sont de deux types.

Tout d'abord au point de vue technologique, l'ensemble du découpeur a été incorporé dans le corps du moteur de pompe ce qui réalise un excellent blindage. D'autre part, des filtres ont été placés dans les lignes d'alimentation du transistor de puissance et dans la ligne de retour à la masse du moteur.

Au point de vue de la fonction de transfert de l'ensemble découpeur, nous avons déjà noté que le filtre, placé dans la boucle de retour, est du 2ème ordre. Le régulateur, quant à lui, est un réseau intégrateur qui annule l'erreur statique et assure un déphasage nul pour les fréquences élevées. Ce dernier point est particulièrement important du fait que le filtre du deuxième ordre apporte un déphasage pour les fréquences élevées.

5.2.3. Régulation

Celle-ci comporte, en réalité, deux éléments différents :

- d'une part, une régulation, au sens strict du terme, qui assure que le paramètre régulé, dans notre cas la vitesse de rotation de la turbomachine, est bien égal à la consigne,
- d'autre part, un réseau d'élaboration de consigne qui, à partir d'un certain nombre de paramètres qui peuvent être soit des réglages, soit des variables comme la vitesse de rotation, soit des affichages de commande, élabore la consigne qui sera comparée à la vitesse vraie à l'entrée du régulateur.

5.2.3.1. Convertisseur fréquence tension et régulateur P I.D.

Nous passerons rapidement sur les éléments du régulateur proprement dit et du convertisseur fréquence-tension qui ne présentent pas d'originalité particulière. La mesure de la vitesse est réalisée, à partir du signal fourni par un capteur à reluctance variable, par un convertisseur fréquence-tension classique. Celui-ci comprend :

- un amplificateur de mise en forme
- un réseau pseudo-dérivateur
- un monostable
- un filtre adaptateur d'impédance réalisé d'une manière similaire à celui utilisé dans le découpeur.

A la sortie, on obtient une tension continue, fonction de la fréquence du signal délivré par le capteur, ayant une très bonne linéarité et un taux d'ondulation résiduelle très faible. Le régulateur P.I.D. est, lui-aussi, très classique. Il fait subir au signal d'erreur, qui naît de la comparaison de la consigne et de la tension fournie par le convertisseur fréquence-tension :

- une amplification de gain K (proportionnel)
- une intégration de constante de temps τ (intégral)
- une avance de phase de même constante de temps τ (dérivation)

Il faut noter que ce régulateur P I.D., employé seul, présenterait de nombreux inconvénients. Examinons, par exemple, ce qui se passe au début du démarrage :

- la consigne externe est maximale
- la vitesse est nulle

L'erreur à l'entrée est donc maximale. Le régulateur P.I.D. va donc voir sa tension de sortie croître jusqu'à sa valeur maximale, c'est-à-dire jusqu'à la valeur de sa propre tension d'alimentation. Le condensateur de l'intégrateur va se charger sous cette tension et on est conduit à une saturation. Celle-ci ne cessera que lorsque le condensateur sera complètement déchargé ce qui peut prendre un temps suffisamment long pour que la machine passe en survitesse compte-tenu de ses faibles temps de réponse. C'est pour cette raison que l'on recherche toujours à se placer dans le cas où l'erreur est très petite D'autre part, il ne faut pas oublier que de tels phénomènes peuvent conduire à des taux d'accélération inacceptables tant du point de vue mécanique que du point du vue thermodynamique.

5.2.3.2. Elaboration de consigne

Le réseau d'élaboration de consigne décrit à la planche 7 agit dans trois domaines qui, tout en étant distincts, sont liés les uns aux autres :
- le contrôle d'accélération
- la limitation de la tension de sortie en fonction de la vitesse
- la limitation de la tension minimale de la tension de sortie

5.2.3.2.1. Contrôle d'accélération

La consigne "vraie" peut être un signal fixe ou variable, cette variation pouvant elle-même être pseudo-continue (par exemple potentiomètre de commande de vitesse) ou par échelon (commande ralenti - plein-gaz). Le trigger d'entrée est un amplificateur à très grand gain qui ne peut avoir que trois états de sortie :

- être à la tension d'alimentation positive, ce qui est obtenu lorsque le signal sortant du sommateur placé à son entrée est positif
- être au zéro lorsque le sommateur lui fournit une tension nulle
- être à sa tension d'alimentation négative ce qui est obtenu lorsque le signal sortant du sommateur placé à son entrée est négatif

Le signal de sortie du trigger est envoyé, à travers un réseau diviseur à l'entrée de l'intégrateur. Si celui-ci reçoit un "plus", il fournit en sortie une rampe croissante de pente constante, puisque la tension à son entrée est constante. Cette pente est d'ailleurs réglable de manière à pouvoir s'adapter aux différentes turbomachines. Si la tension d'entrée passe par zéro, il reste à la tension où il se trouvait. Si la tension d'entrée est négative, il fournit en sortie une rampe décroissante. On remarque que la sortie de l'intégrateur est rebouclée sur le sommateur placé devant l'intégrateur, ce qui permet d'arrêter la rampe lorsque celle-ci a atteint le niveau de la consigne vraie.

Grâce à ce dispositif, tout échelon de consigne vraie sera transformé en rampe croissante ou décroissante suivant le sens de variation de l'échelon. On peut voir que les deux autres lignes arrivant à l'entrée de l'intégrateur permettent de limiter par valeur maximale ou par valeur minimale le signal issu du trigger. Nous montrerons l'utilité de ces limitations plus loin.

Une fois que l'action de limitation sera terminée, on obtiendra en sortie de l'intégrateur une rampe. C'est cette rampe qui sera comparée à la vitesse afin de commander la régulation. Le dispositif fonctionne alors de deux manières légèrement différentes suivant la phase de fonctionnement où l'on se trouve.

Trois cas peuvent se présenter :

1er cas : la machine accélère normalement et suit la rampe de sortie du générateur de consigne interne. Dans ce cas, le système fonctionne de la même façon en tout point, du démarrage au plein gaz, et en chaque point la vitesse est régulée par le P.I.D. au point considéré.

2ème cas : la machine accélère trop vite. Dans ce cas, la grandeur de sortie diminue sous l'action du régulateur jusqu'à la valeur du "mini-pompe" (cf. § 5.2.3.2.3.).

3ème cas : la machine n'accélère pas ou faiblement. Dans ce cas, la grandeur de sortie augmente sous l'effet du régulateur jusqu'au moment où elle atteint la valeur de limitation (cf. § 5.2.3.2.2.). A partir de ce moment, la consigne interne est ramenée à la valeur de la vitesse et elle y restera jusqu'à ce que la machine accepte d'accélérer. La consigne interne sera alors libérée selon la rampe de sortie de son dispositif d'élaboration. On voit donc que dans ce fonctionnement, l'accélération est limitée à une valeur supérieure.

Lorsque l'on commande une variation de vitesse à partir d'un régime [illegible] bli par exemple en effectuant une commande ralenti-plein gaz ou inversement, la régulation va faire en sorte que l'écart entre la vitesse et la consigne interne reste nul, ce qui revient à dire que la courbe d'évolution de la vitesse va suivre celle de la consigne et ceci constitue, en fait, une régulation d'accélération et de décélération.

5.2.3.2.2. Limitation de la valeur maximale de sortie

Le dispositif fonctionne de la manière suivante. On additionne :
- une tension fixe, nommée "seuil" avec
- une tension proportionnelle à la vitesse de rotation et nommée, improprement d'ailleurs, "limitation", et on compare cette somme à la tension de la grandeur de sortie.

L'erreur est amplifiée, puis envoyée à l'intégrateur d'élaboration de consigne par l'intermédiaire d'une diode. Cette diode est polarisée de manière à ce qu'elle soit :
- passante dans le sens intégrateur vers amplificateur de limitation
- bloquée dans le sens inverse

Ceci veut dire que la diode sera passante lorsque l'ampli de limitation demandera une diminution, c'est-à-dire lorsque la tension de la grandeur de sortie sera plus grande que la somme du "seuil" et de la "limitation". La diode en devenant passante fait en sorte que la tension de sortie du régulateur soit égale à U "limitation" + U "seuil". En sens inverse, c'est-à-dire lorsque la grandeur de sortie est plus petite que la somme du "seuil" et de la "limitation", l'ampli de limitation demandera une augmentation, la diode se bloque et ce circuit n'intervient plus. On aura donc toujours U sortie < (U "limitation" + U "seuil"). La valeur de U "seuil" est réglable au niveau du boîtier de même que U "limitation". De plus, on peut, par commutation, neutraliser l'action de U "limitation" jusqu'à un certain seuil de vitesse.

Voyons maintenant l'utilité de ce circuit. Plaçons nous d'abord à l'instant du début de démarrage :
- la vitesse est nulle, donc U "limitation" est nul
- la grandeur de sortie est nulle

La sortie du trigger étant au plus, l'intégrateur commence à fournir une rampe. Celle-ci est envoyée au régulateur P.I.D. qui la reçoit en totalité puisque la vitesse est nulle.

Ceci fait donc immédiatement monter la grandeur de sortie, avant même que la vitesse n'augmente. Dès que la tension de sortie est égale au "seuil", la diode devient passante. Si l'on veut que la grandeur de sortie du régulateur reste limitée au seuil, il faut que le sommateur d'entrée du P.I.D. soit à zéro, c'est-à-dire que la consigne interne soit égale à la vitesse.

La vitesse ayant une certaine valeur, il faut que la consigne interne baisse et pour cela, il suffit que le condensateur d'intégration du circuit d'élaboration de consigne se décharge à travers la diode. La constante de temps de cette décharge étant environ 100 fois plus faible que celle de l'intégration, on constate une chute rapide de la consigne interne. Celle-ci s'arrête à une valeur telle que la vitesse soit égale à la consigne interne (si cela est possible compte-tenu du réglage de la valeur minimale : cf § suivant). Ce dispositif permet donc, pendant les premiers instants, d'injecter ce qu'il faut pour allumer et, si la vitesse ne monte pas, d'injecter un minimum de carburant

Si nous nous plaçons à une vitesse quelconque, non nulle, U "limitation" vient se rajouter à U "seuil" et le fonctionnement est similaire. Ceci signifie donc qu'à toute vitesse correspond une grandeur maximum de sortie qui ne peut être dépassée.

5.2.3.2.3. Limitation de la valeur minimale absolue de la sortie

On sait que tout moteur électrique a besoin d'une tension minimale à ses bornes pour démarrer. Or, il peut se faire, dans les transitoires de régulation, que la tension de sortie soit nulle. Le moteur aurait tendance à s'arrêter avant que cette valeur soit atteinte et ne pourrait repartir qu'au-dessus d'une certaine tension.

Par exemple, au début du démarrage, si le moteur électrique de lancement fournit une accélération supérieure à l'accélération maximale autorisée par le boîtier, la tension de sortie irait à zéro. Pour éviter cela, on a muni le système d'une limitation basse qui, en tout état de cause, imposera à la tension de sortie une valeur minimale en dessous de laquelle on ne pourra descendre : "le mini-pompe".

Le dispositif est similaire à celui de la limitation maximale, mais, bien entendu, la diode qui permet le raccordement sur l'entrée de l'intégrateur de l'élaboration de consigne est polarisée en sens inverse. Il faut bien noter que cette tension minimale imposée au moteur correspond à une vitesse de rotation minimale, donc à un débit minimal.

6. MISE AU POINT ET RESULTATS OBTENUS

Les travaux de mise au point ont débuté par la détermination des réglages optimaux du clapet différentiel. En particulier, ainsi que nous l'avons dit précédemment, il faut tenir compte de toutes les pertes de charge du circuit de retour réel qui déplacent le début de la courbe $Q_I = f\ (Up)$. Nous avons aussi recherché s'il était intéressant de modifier le gain très important autour du point de régulation nominal. Cette action est possible mais peu intéressante car la marge de gain du système est largement suffisante. Les réglages du régulateur électronique sont faciles et classiques. Le seul point intéressant est la recherche de la valeur du gain proportionnel compatible avec tous les types de fonctionnement. Il importe en effet de bien vérifier l'action de toutes les perturbations possibles. On peut voir sur le schéma de la planche 8 que ces perturbations sont fort nombreuses et agissent sur plusieurs équipements.

En ce qui concerne le G.A.P., l'accélération maximale tolérée peut prendre deux valeurs : à basse vitesse on autorise une accélération plus faible car on n'a pas d'obligation particulière en ce qui concerne le temps de démarrage. Les résultats obtenus tant en conditions simulées qu'en utilisation réelle sont très bons tant au niveau de la fiabilité qu'au niveau des performances. Le système de démarrage a accumule maintenant plusieurs milliers de cycles dans toutes les conditions d'environnement. On a surtout remarqué la sureté du démarrage à très basse température grâce à l'emploi du "pulse" au démarrage.

Le groupe autonome de puissance a démontré en utilisation réelle une enveloppe de fonctionnement beaucoup plus large que celle prévue tant dans le domaine de l'altitude, puisque l'altitude de 12 000 mètres a pu être atteinte, que dans le domaine des températures extrêmes, puisque des démarrages ont pu être tentés avec succès jusqu'à des températures de - 45°C, à l'aide des seules batteries alors que le domaine normal de démarrage est limité à - 30°C

7. CONCLUSION

Le nouveau système de commande de débit de carburant a démontré en utilisation une très bonne fiabilité et de bonnes performances. Sa simplicité en fait un produit facile à fabriquer et à régler, donc ayant un prix de revient compétitif.

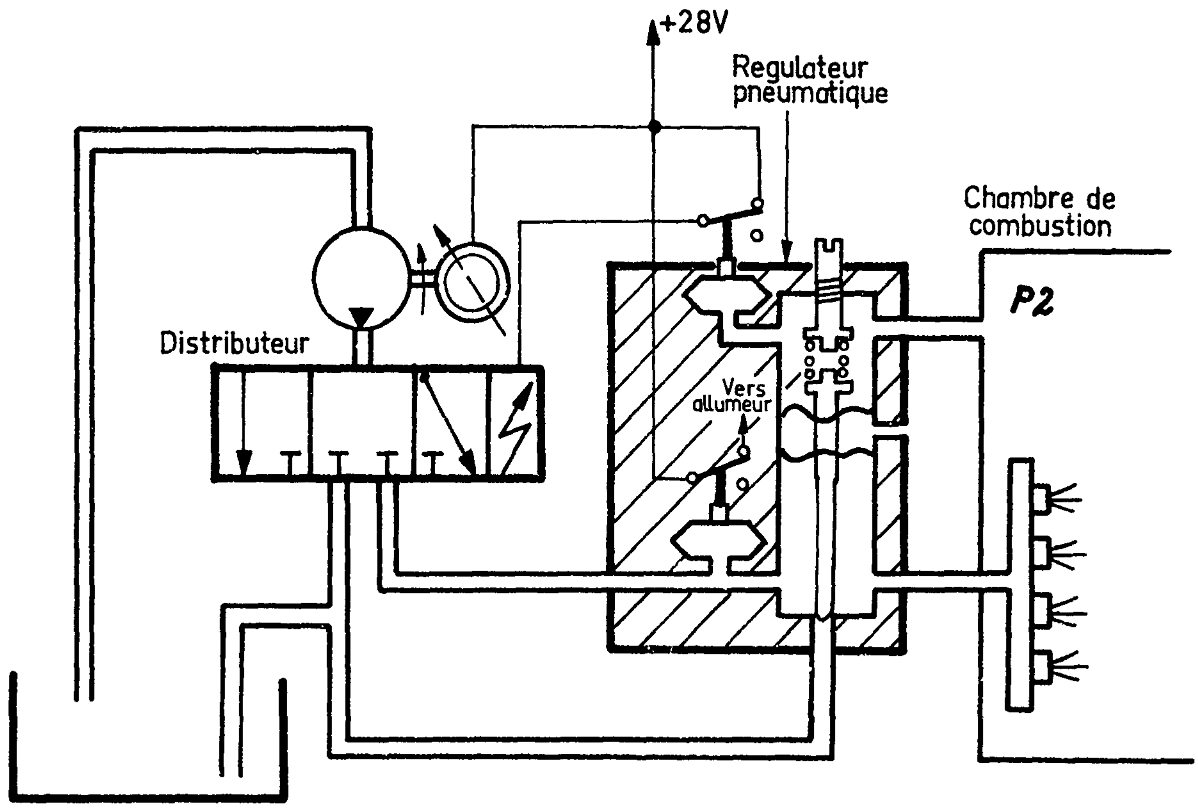


Planche 1 : Système pneumatique

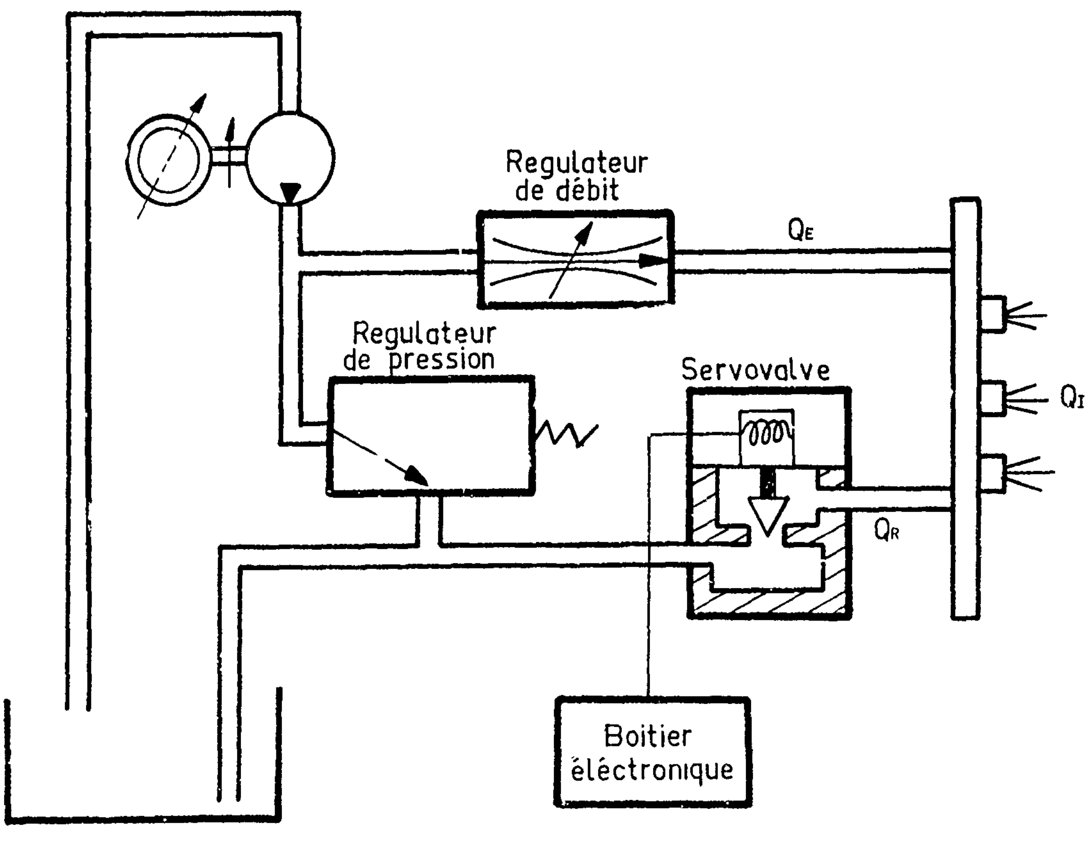


Planche 2 : Système à électropompe et servovalve

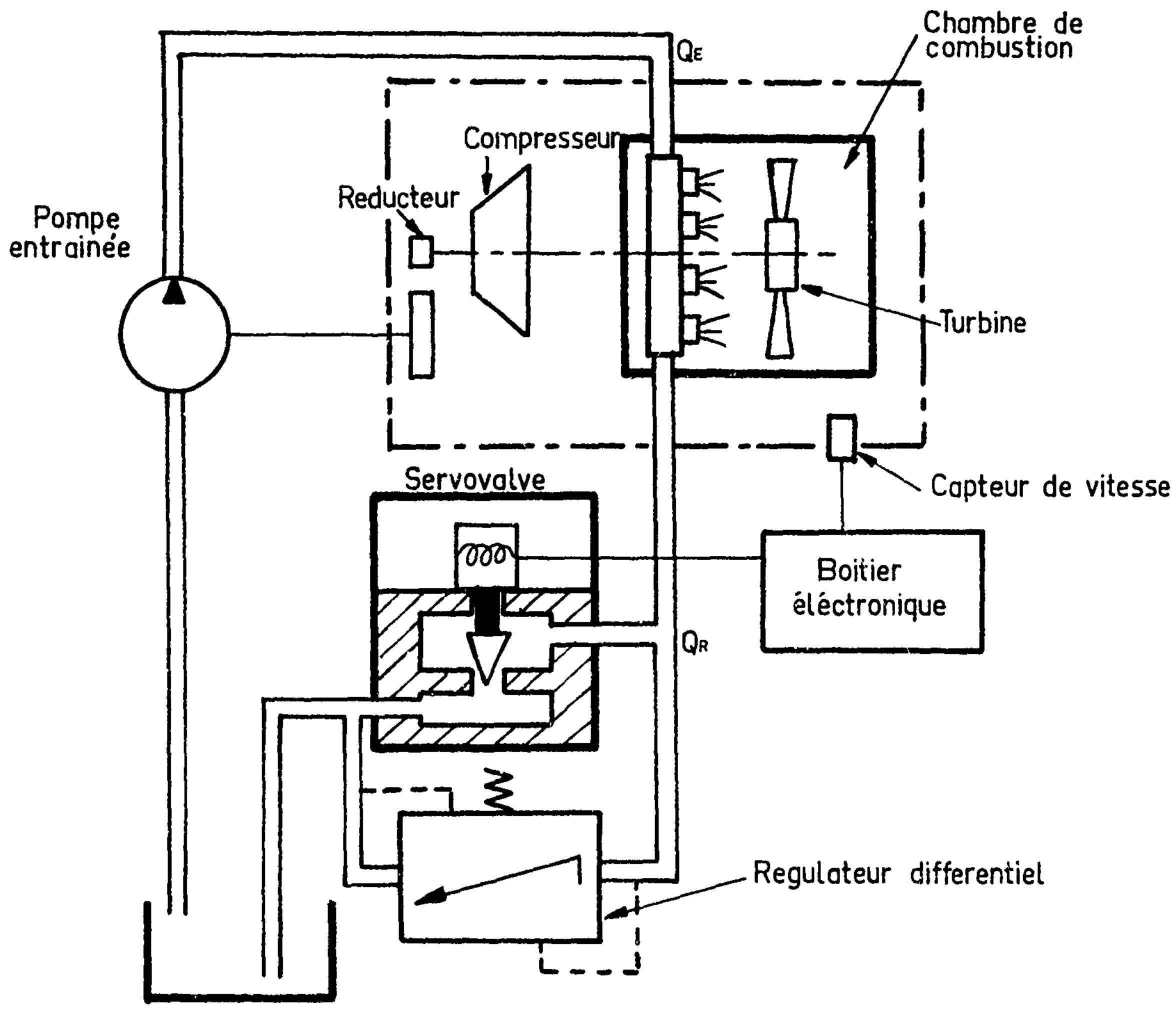


Planche 3 : Système à servovalve et pompe entraînée

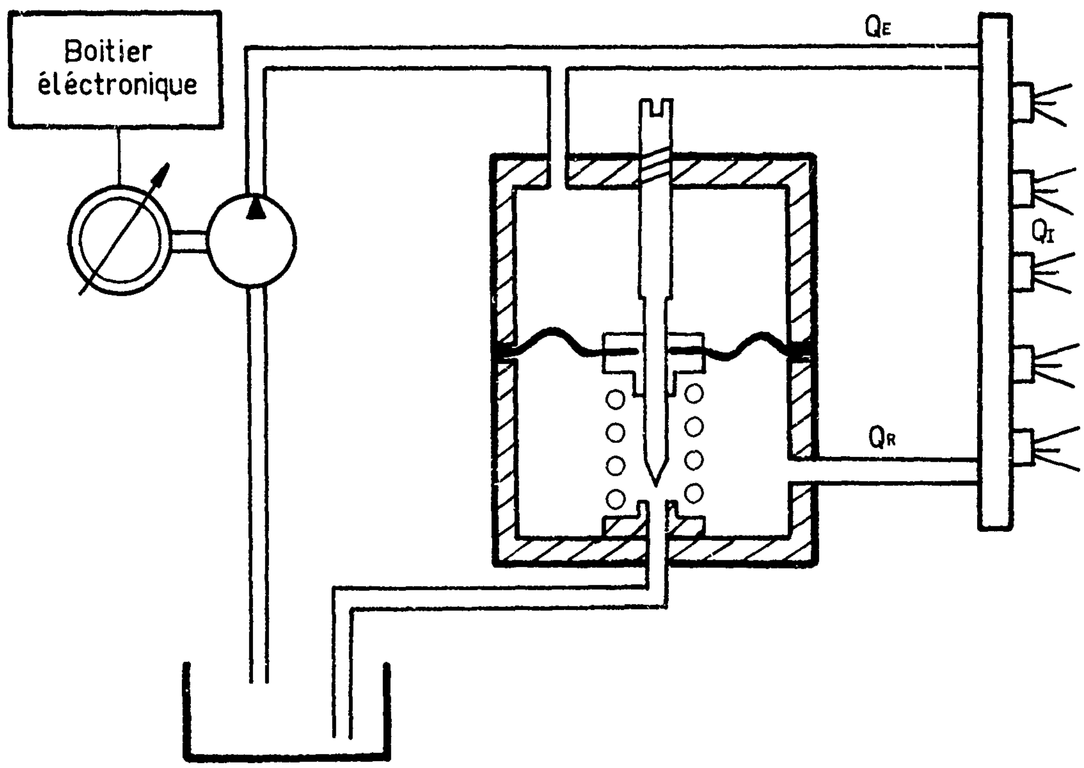


Planche 4 : Système à découpeur et clapet différentiel

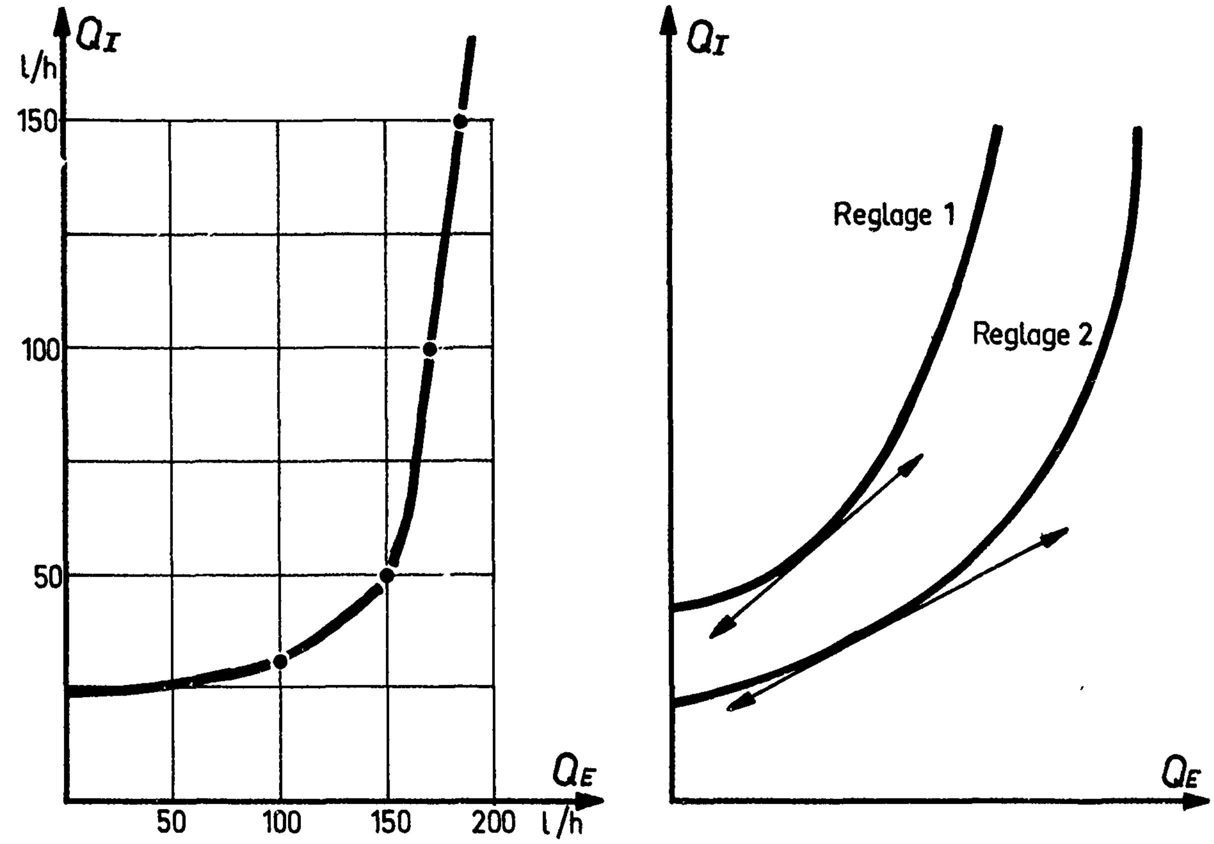


Figure 5 : Courbes Q_I = f (Q_E), F (U_p)

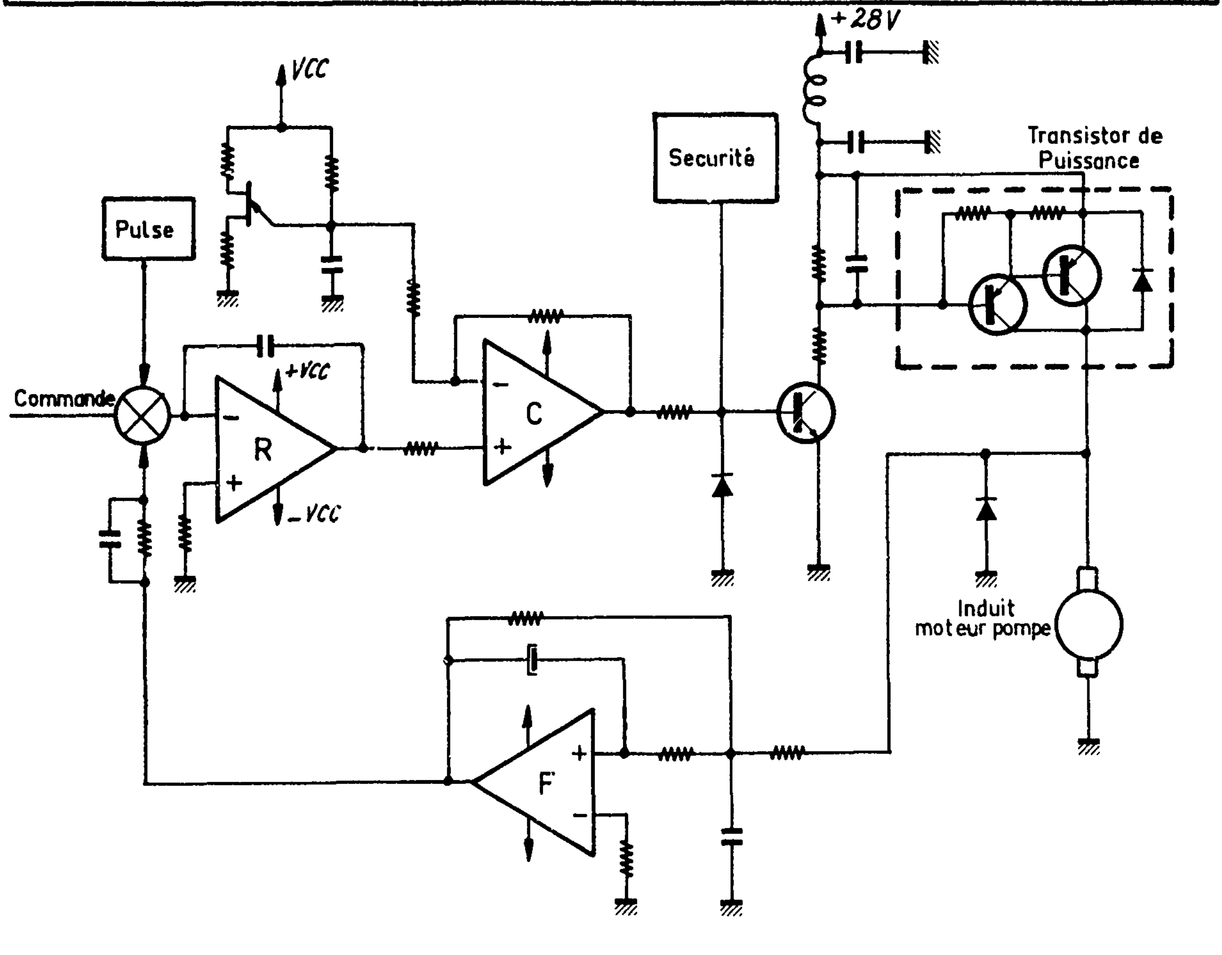


Figure 6 : Schéma bloc du découpeur

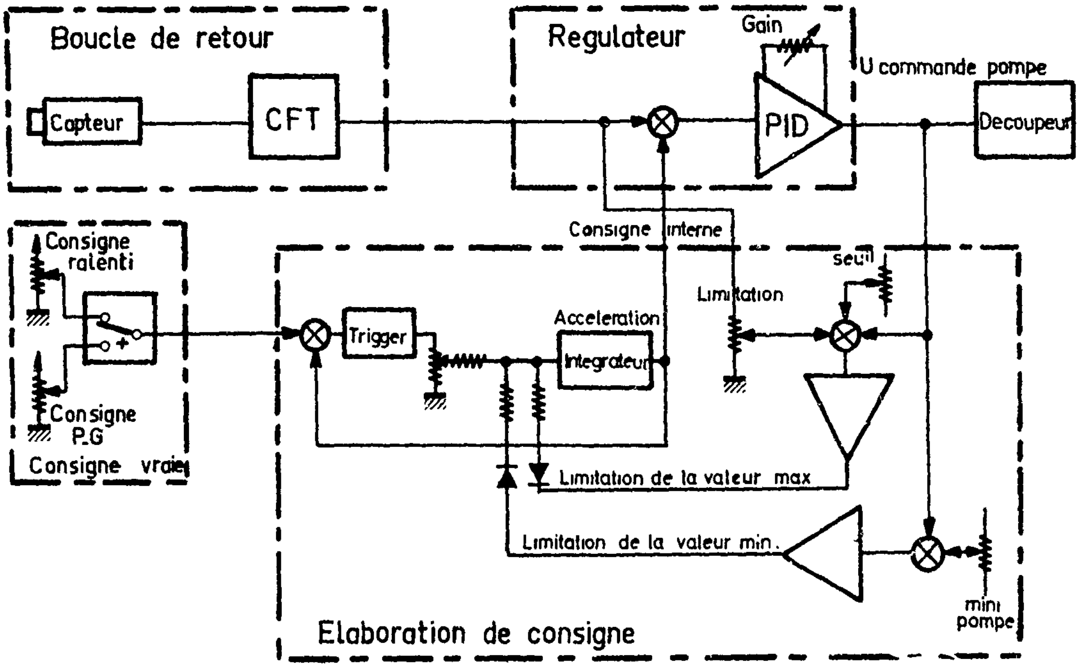


Planche 7 : Disposition d'élaboration de consigne

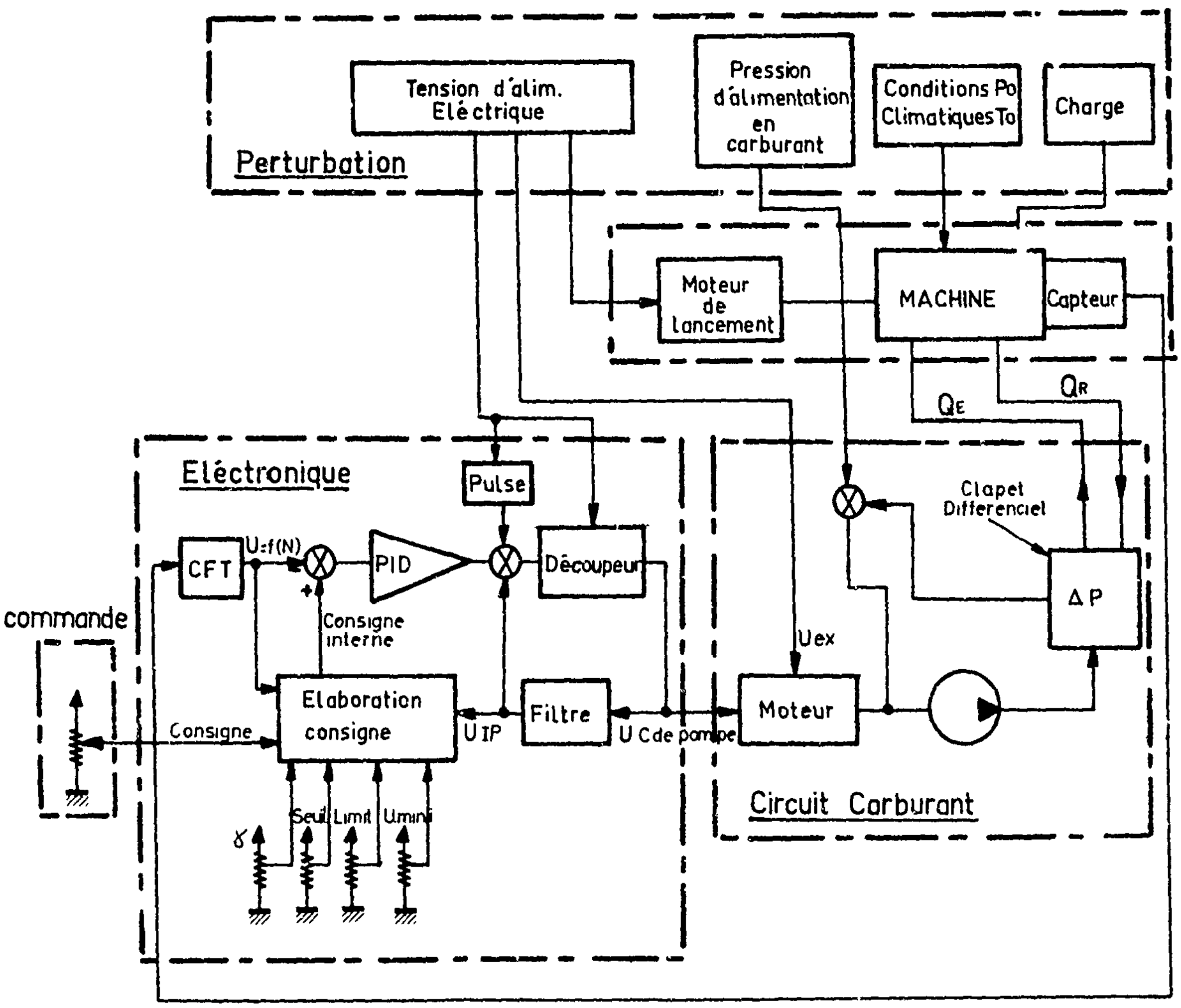


Planche 8 : Schéma bloc d'ensemble

DISCUSSION

Prof. Amoia, It

There is a definite trend in today technology towards digital control. You have preferred an analog solution. Would you please comment on the motivation of your choice.

Author's Reply

(1) Pour une fabrication en petites quantites les systemes analogiques sont, encore actuellement, beaucoup moins chers.

(2) D'autre part nous avons voulu d'abord verifier le fonctionnement de ce système, dont l'étage de puissance est pratiquement numerique puisque commandé par des creneaux, avec une régulation analogique bien connue. Il est dans notre intention d'utiliser, dans un proche avenir, une régulation numérique.

Translation

(1) Analog systems are still appreciably cheaper for small production quantities.

(2) Apart from this, we first of all wanted to check the operation of this system, whose power stage is practically numerical, as it is controlled via teeth (serrations, cams) with a well-known analog control. We intend utilising numerical control shortly.

TRANSDUCERS FOR ENGINE CONTROL SYSTEMS

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SUMMARY

The analysis of engine control requirements shows that two types of parameters must be measured. Non-dimensional parameters are required for performance and handling work, whereas dimensional parameters such as pressure and temperature are required for structural protection.

Conventional transducers measure the dimensional or structural parameters which means that the non-dimensional performance terms must be computed from the structural parameters. This leads to inaccuracies, particularly at high altitude where the dimensional quantities may represent only a small percentage of the transducer scales, and because of this the system designer may be forced to chose non-optimum parameters for the control system.

This paper describes some active fluidic transducers which measure the fundamental non-dimensional quantities required for engine control systems. The use of these transducers offers a true non-dimensional measurement of engine performance and allows the system designer a freer choice of control parameters.

SYMBOLS

K	Arbitrary Constant
N	Shaft Speed
T	Air Temperature (Total)
W	Air Mass Flow
P	Air Pressure (Total)
p	Air Pressure (Static)
M	Duct Mach number
γ	Ratio of Specific Heats
A	Duct Cross Sectional Area
Rg	Gas Constant

Suffices 1 and 2 represent arbitrary stations in the engine

1. INTRODUCTION

The first gas turbine engine controls were simple systems using shaft speed, corrected by inlet air temperature, as the main parameter. This was a natural follow-on from the control of piston engines, on which speed was of primary importance. Control system development followed from these beginnings, and led to the extensive use of hydro-mechanical controls using normalised speed, $N/\sqrt{T}$ as the control parameter. Later developments introduced pressure ratio as a parameter, but the mechanisation of the control was aga by hydro-mechanical means with limited computational capability. As engine performance requirements have become more stringent, with the need for higher performance and efficiency, so control systems have had to become more precise and have had to manage more parameters. This is especially so on supersonic aircraft where flight parameters may be included in the overall control equations.

With the development of digital electronic computers having high speed and great computational capacity there has been natural trend towards full digital control of engines. This approach has allowed all relevant parameters to be considered in the control equations, but equally this imposes a demand for many more transducers. A simple block diagram of a control system is shown in Figure 1, and it is clear that input transducers are required to supply information to the computer, whilst output transducers are required to enable the computer to control the engine.

This paper discusses some particular input transducers specifically designed for aircraft engine control systems.

2. CONTROL PARAMETERS

Analysis of engine control requirements shows that two types of parameters must be considered for complete and effective control. These are, performance parameters, and structural parameters as shown on Figure 2. Performance parameters are the non-dimensional or normalised quantities used to measure the thermodynamic performance and stability of the engine. These are:-

Normalised Speed	$N/\sqrt{T}$
Pressure Ratio	P_2/P_1
Normalised Mass Flow	$\frac{W\sqrt{T}}{P}$
Temperature Ratio	T_2/T_1

Structural parameters are the dimensional quantities relating to the strength and life of the engine and are used simply to set performance limits. They are:-

Shaft Speed	N
Temperature	T
Pressure	P

Conventional transducers measure the structural parameters directly, since they usually make use of physical effects generated by these quantities. For example in a pressure transducer, the pressure to be measured is used to deflect a diaphragm which causes an electrical element to be distorted, and this in turn produces an electrical signal proportional to the pressure causing the distortion. This pressure, which can cause distortion of the engine structure, is measured by making use of the same effect in the transducers.

Temperature measurement utilises a direct physical effect although in a somewhat different manner. Conventional temperature sensors rely on a direct thermal to electric effect, either in a thermocouple or in a resistance thermometer. Measurement of shaft speed, which is necessary to prevent overstressing of of rotating parts, also originally depended on centrifugal effects on flexible sensors, although direct measurement of speed is now accomplished by the use of inductive and optical sensors which transduce speed into frequency of an electrical or optical signal.

It is clear, therefore, that conventional transducers provide a direct means of converting the structural parameters into electrical signals suitable for input via analogue-to-digital converters into the computer.

With this background, and the power of the digital computer, it is natural that the current control system design philosophy is to compute the performance parameters from the structural parameters. However, this is not such a simple process as it might appear, and it is appropriate at this point to look in more detail at the problems involved.

2.1. $N/\sqrt{T}$

This requires measurements of shaft speed N, and air temperature T to be made. Shaft speed is easily measured using an inductive or optical probe to produce an electrical signal whose frequency is proportional to speed. Air temperature measurement, however, depends on heat transfer from the air stream to the sensing element, usually a thermocouple before the measurement is effective. Thermocouple response can be reduced to fractions of a second and good results can be obtained where temperature fluctuations are not too rapid to be followed successfully. However, in modern multi-shaft engines, it may be desirable to use the air temperature at some intermediate position in the engine, for example at the inlet to the third spool of a three shaft engine, and the rate of change of air temperature may reach 100°C per second during rapid acceleration or deceleration. The accuracy of the measurement in these circumstances, even with computerised compensation, is usually unacceptably low.

This problem is aggravated by the fact that $N/\sqrt{T}$ is a very non-linear performance parameter. Idling thrust may occur at 40% to 50% of maximum $N/\sqrt{T}$, and the range from half to full thrust may occur between 85% and 100% of maximum $N/\sqrt{T}$. Clearly, to obtain good performance control, a very high accuracy is required in the measurement of $N/\sqrt{T}$. Engine intake temperature is, therefore, used as the parameter in order to obtain a more steady and hence more accurate reading. However, this approach not only sacrifices information about the core of the engine, but also poses the problem of preventing ice formation on the sensing element in adverse weather conditions.

Nevertheless, because of the historical use of engine speed, $N/\sqrt{T}$ is still often used as a preferred parameter in spite of these difficulties.

2.2. P_2/P_1

Pressure ratio requires the measurement of two pressures and may be computed in the form P_2/P_1 or as $1 + \frac{\Delta P}{P_1}$ where $\Delta P = P_2 - P_1$. This is an ideal parameter for monitoring engine performance since it has an approximately linear relationship with thrust. Furthermore, the response time of the measurement is effectively independent of where in the engine the measurement is taken. It is, therefore, possible to monitor pressure ratio in several places and deduce the "state of health" of the engine in addition to controlling performance.

The major problem in pressure ratio measurement concerns the accuracy obtainable at high altitude This is best illustrated by the following example. Suppose overall compressor pressure ratio is being measured on a modern high efficiency engine where the maximum ratio is 30:1 and the accuracy required is $\pm$ 2%. At sea level the compressor delivery pressure will be a maximum of 3040 KPa and so the appropriate pressure transducer must be capable of measuring this pressure. However, if the aircraft is able to operate at an altitude of 16 km where the atmospheric pressure is about 10% of the sea level value, all the pressures in the engine will be similarly reduced to 10% of their sea level values. The maximum compressor delivery pressure will then be 304 KPa, and if the engine is throttled back for descent, the pressure may fall to only 150 KPa. For an overall accuracy of $\pm$ 2% in pressure ratio, each pressure must be measured to better than $\pm$ 1%. If the extreme altitude situation is to be catered for, the transducer connected to compressor delivery pressure must measure 150 KPa to an accuracy of $\pm$ 1%, i.e. to $\pm$ 1.5 KPa. This same transducer at sea level must equally be able to measure up to 3040 KPa, so the accuracy specificatiion for this transducer requires $\pm$ 1.5 KPa in 3040 KPa, i.e. better than $\pm$ 0.05% of full scale. This accuracy must be met over the full range of working temperature and energising voltage. Clearly this is a difficult task, and similar requirements apply to all other pressure transducers used for measuring pressure ratio.

2.3. $W\sqrt{T}/P$

Logically, this requires measurements of air mass flow, temperature and pressure, but as mass flow would require the entire engine air flow to be measured an alternative approach has to be taken. The normal method is to relate $\frac{W\sqrt{T}}{P}$ to the flow Mach number at a suitable station in the engine and then to deduce the Mach number from the ratio of total to static pressure. The problem then reverts to pressure ratio measurement and is covered by the comments in the previous section.

2.4. T_2/T_1

The problems associated with fast, accurate temperature measurement have already been covered in Section 2.1. and because of these, temperature ratio is not generally used as a performance parameter. It could, however, have significant value in engine health monitoring, for example, if both pressure ratio and temperature ratio across a compressor are measured, deterioration will become evident by a rise in temperature ratio for a given pressure ratio. In this situation, steady state measurements are adequate and so the problems are minimised.

2.5.

From the foregoing, it is clear that $N/\sqrt{T}$ is often used as the main performance parameter because of historical development, and because of the difficulty in measuring the alternative parameters using conventional structurally oriented transducers. In consequence, information regarding engine performance is lost and deterioration of efficiency with age cannot be detected. The use of pressure ratio in conjunction with normalised mass flow or with temperature ratio would provide a full knowledge of the engine performance, together with an indication of its efficiency or "state of health." This approach would also give a much more linear control since pressure ratio has a nearly linear relationship with thrust whereas $N/\sqrt{T}$ does not.

If this approach is to be used effectively it is, therefore, necessary to have available an accurate means of transducing pressure ratio into an electrical signal, suitable for a computer input.

3. THE PRESSURE RATIO TRANSDUCER

From the earlier discussion it was apparent that the computation of pressure ratio from individual pressure measurements gave rise to considerable inaccuracies because of the wide range of pressure variation with altitude. It was, therefore, decided to utilise the fundamental properties of compressible flow to generate a signal which would be purely a function of pressure ratio, without being dependent on the actual pressure level or altitude. The mechanisation of this concept was achieved through the use of fluidics.

3.1.

Figure 3 shows a block diagram of the Pressure Ratio Transducer (PRT) which consists of an engine mounted unit plus an airframe mounted amplifier or Pressure Ratio Processing Unit (PRPU).

A fluidic oscillator, driven from the pressure P_2 generates a triangular output pressure waveform as shown in Figure 4A. This is passed into a modulator element which takes the form of a multi-input switch. The modulator is driven from P_2 but receives an additional input from P_1 pressure. In the absence of any pressure ratio information, the modulator would switch at the zero crossing points of the oscillator waveform as shown in Figure 4B, giving rise to a rectangular pressure waveform of 50% duty cycle. The pressures P_2 and P_1 act on the secondary inputs of the modulator in such a way as to bias the switching point above or below the zero line on the triangular waveform, by an amount proportional to the ratio P_2/P_1. This has the effect of changing the duty cycle of the modulator output as shown in Figure 5. The pressure ratio information has thus been converted into a pulse width modulation of the modulator output. This is then transduced into an electrical signal by means of pizo-electric crystals, and this signal is transmitted by cable to the PRPU.

In the PRPU the low level signal is amplified and converted from a pulse width modulated signal into an output suitable for use in a computer or other electronic control system. In current applications the output is in the form of an analogue voltage in the range 1 to 6 volts, but this could alternatively be presented as a digital signal by a suitable alteration to the PRPU circuitry.

The engine mounted unit is shown in Figure 6, and the fluidic oscillator and modulator can be clearly seen. Also visible is the electrical connector which covers the piezo electric crystal housing. The three pipe flanges provide connections to P_2, P_1 and a vent spill pipe. The PRPU, mounted in the airframe is illustrated in Figure 7. It is shown here as a separate unit but could equally be accommodated as a card in the computer installation.

The current standard of PRT is designed to measure pressure ratio in the range P_2/P_1 = 5 to 10, plus a reduced accuracy range up to P_2/P_1 = 15. With minor modifications the overall range can be altered upwards or downwards by approximately 50%. By the use of the fluidic technology, the unit measures pressure ratio as a fundamental parameter, and is, therefore, able to offer a measurement accuracy of $\pm$ 2% over an altitude range of sea level to 18 km. The fluidic unit is mounted directly on the engine and is designed to operate at a temperature in excess of 300°C. This limit is imposed only by the Piezo-electric crystals and the electrical insulation, and an experimental unit has run successfully at a temperature of 450°C. A typical calibration is shown in Figure 8, and an accuracy plot is given in Figure 9.

The development of the pressure ratio transducer enables pressure ratio to be measured as a fundamental performance parameter with constant accuracy over the engine operating range. In consequence a new dimension has been added to control system design.

4. NORMALISED MASS FLOW

From compressible flow relationships it can be shown that the ratio of total to static pressure in duct is related to the flow Mach number in the duct by the expression:

$$\frac{P}{p} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma - 1}}$$

which for air ($\gamma = 1.4$) reduces to:

$$\frac{P}{p} = (1 + 0.2\, M^2)^{3.5}$$

It can also be shown that the mass flow in the duct is related to the Mach number by the expression:

$$W = \frac{\upsilon PA}{\sqrt{\gamma RgT}} \times \frac{M}{\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{(\gamma + 1)}{2(\gamma - 1)}}}$$

which for air reduces to:

$$W = \frac{1.1832\ PA}{\sqrt{RgT}} \times \frac{M}{(1 + 0.2\, M^2)^3}$$

$$\text{i.e.}\quad \frac{W\sqrt{T}}{P} = \frac{1.1832\ A}{\sqrt{Rg}} \times \frac{M}{(1 + 0.2\, M^2)^3}$$

The term $\frac{1.1832\ A}{\sqrt{Rg}}$ is constant for any given position in the engine. Hence:

$$\frac{W\sqrt{T}}{P} = f_1\ (M)$$

and since $M = f_2\ (P/p)$

Then:

$$\frac{W\sqrt{T}}{P} = f_3\ (P/p)$$

Hence the normalised mass flow in a duct may be represented as a unique function of total to static pressure ratio P/p.

If the pressure ratio transducer already described is connected to the air in the duct as shown in Figure 10B, the total pressure P replaces P_2 and the static pressure p is divided down by an orifice pair to a value Kp which replaces P_1. The PRT still measures P_2/P_1 which becomes $\frac{1}{K} \cdot \frac{P}{p}$, and so it has now effectively become a transducer for normalised mass flow $\frac{W\sqrt{T}}{P}$. A typical calibration is shown in Figure 11.

A normalised mass flow transducer can, therefore, be offered to provide measurement of a valuable performance parameter which has so far been regarded as difficult to measure. A small limitation in this design is that the resolution is low at very low duct Mach number due to the shape of the calibration curve, but at most normal working conditions good resolution is obtainable.

5. FURTHER DEVELOPMENTS

The normalised mass flow transducer described in the previous section is ideally suited for measurements in the high pressure conditions encountered in engine compressors. It is, however, not suited to measurements in low pressure areas such as engine intakes and fan streams where insufficient pressure is available to drive the fluidic elements. For such situations an alternative approach is required, and use may be made of the ability of the duct flow to deflect a jet of air in a fluidic device as shown in Figure 12.

As was stated in Section 3, the temperature limitation on the PRT is imposed purely because of the piezo-electric crystals and the elctrical insulation. The normal maximum working temperature is 300°C although operation up to 400°C is possible for short periods. Special high temperature piezo-electric material has been tried which has a capability of operating at over 600°C although to date this material has only been tested in a PRT at 450°C because of a test rig limitation. Nevertheless, the capability of modifying the PRT to work at very high temperatures is available and the potential has been successfully demonstrated.

Temperature ratio T_2/T_1 was mentioned in Section 2.4 as a useful parameter in engine health monitoring. Whereas thermocouples could be used to provide the individual temperature measurements, an alternative, and more robust solution is possible using fluidics. Consider air from the compressor at pressure P_2 and temperature T_2 passing through an orifice A, along a duct and through a second orifice B to discharge to vent as shown in Figure 13. If the pressure in the duct is P_D and the temperature is T_D, and if choking flow exists in the orifices A and B it can be shown from simple flow analysis that P_D is related to P_2 by the expression:

$$P_D = \frac{A_A}{A_B} \times \sqrt{\frac{T_D}{T_2}} \times P_2$$

Where A_A and A_B are the areas of the orifices A and B respectively.

If the duct is maintained at compressor inlet temperature T_1 by an external flow as shown in Figure 13, so that $T_D = T_1$ then clearly:

$$\frac{P_2}{P_D} = \frac{A_B}{A_A}\sqrt{\frac{T_2}{T_1}}$$

Hence the ratio P_2/P_D gives a measurement of T_2/T_1. Now the PRT is already available to measure pressure ratios, so if P_D is connected to a PRT in place of P_1 then the PRT output becomes a function of T_2/T_1. This arrangement is shown in Figure 14. Measurement of temperature ratio by this method is not confined to compressors, as the robust nature of the equipment would allow even turbine entry temperature to be used in place of T_1 if desired.

One further development which deserves mention is the possibility of replacing the electrical link between the PRT and the PRPU with an optical link. Some work has been carried out to develop an optical output pressure sensor which can be incorporated into a PRT in place of the piezo-electric crysals. An optical fibre link would then carry the signal to a modified type of PRPU where it would be converted to an electrical signal suitable for use in the electronic control system as at present. The advantage of this development is that the optical link is completely free from any possible electrical interference, and, therefore, it is possible to eliminate from the PRPU the existing interference rejection circuit. This in return releases the fluidic system from a particular frequency constraint and allows it to be worked at its optimum oscillator frequency of 350 to 450 Hz, resulting in a significant improvement in signal-noise ratio and response.

6. CONCLUSIONS

Conventional transducers are designed to measure structural parameters such as shaft speed, air temperature and air pressure. The use of such transducers to determine the engine performance parameters, normalised shaft speed, pressure ratios, and normalised mass flow, leads to an unsatisfactory situation. Pressure ratio, and normalised mass flow are very difficult to measure to an acceptable degree of accuracy, and the use of normalised shaft speed as the main control parameter leads to non-optimum control system design.

A fluidic pressure ratio transducer is available which measures pressure ratio as a fundamental parameter, and thereby offers a direct and accurate measurement over a wide range of operating conditions. The use of this device offers the system designer a means of measuring one of the fundamental engine performance parameters, and opens the door to greater optimisation of system design.

The pressure ratio transducer can, in a modified form, also provide a measurement of normalised mass flow, so that a second fundamental performance parameter can be monitored. Further developments include the possibility of using the basic transducer to measure temperature ratio for engine health monitoring, and also the development of an optically coupled unit having an improved signal-noise ratio and a faster response.

7. ACKNOWLEDGEMENTS

The author wishers to thank his colleagues for their assistance in preparing this paper, and the Directors of Plessey Aerospace Limited for perm sion to publish it.

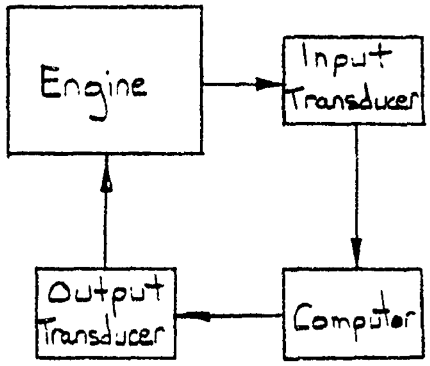


Fig. 1.
Control System Block Diagram

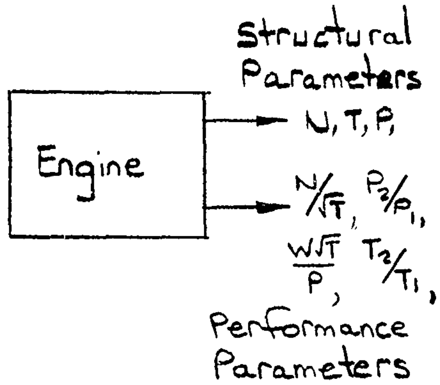


Fig 2.
Engine Parameters

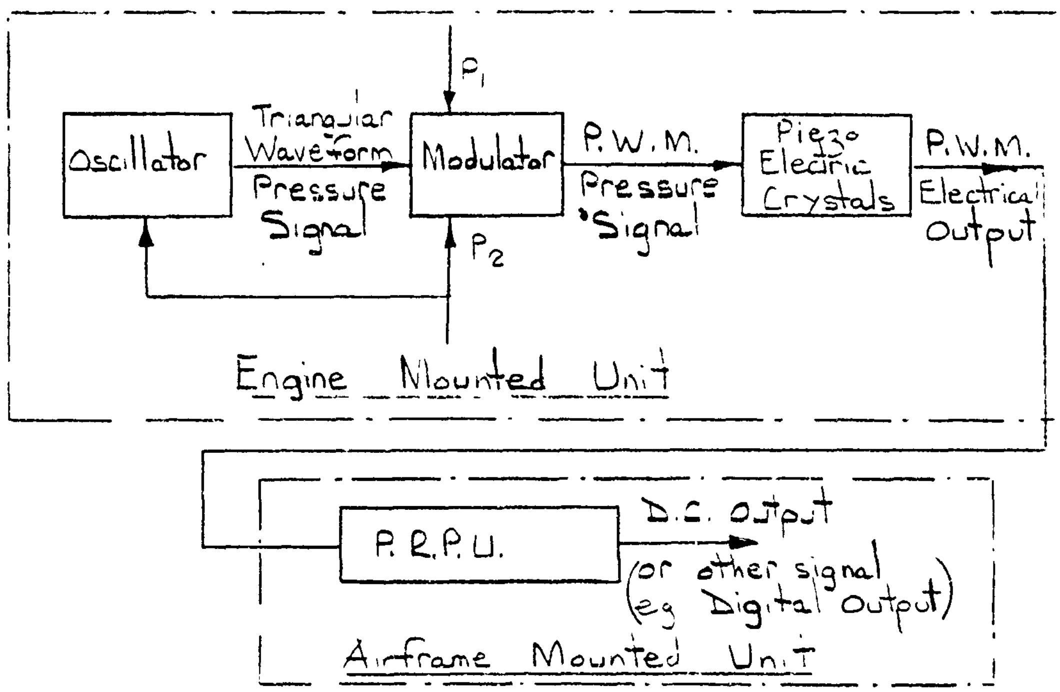


Fig 3.
Pressure Ratio Transducer Block Diagram

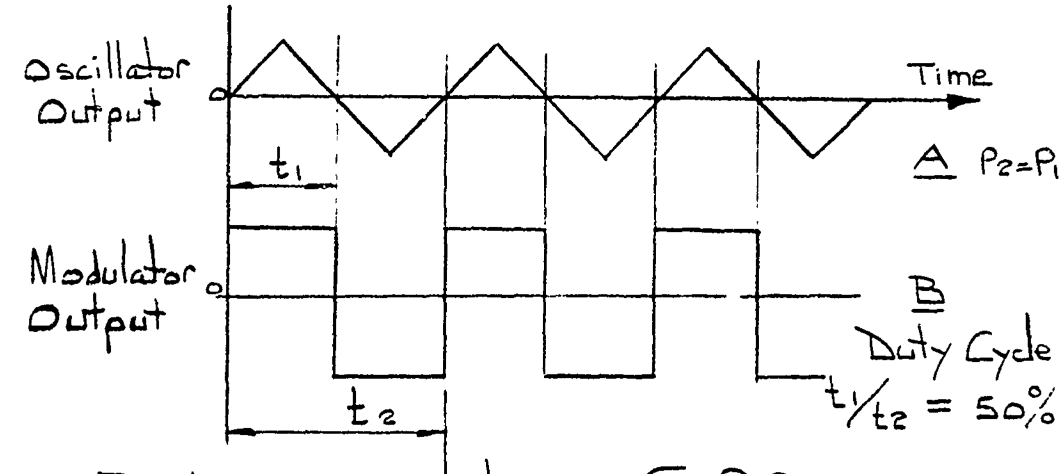


Fig 4 Operation of P.R.T.

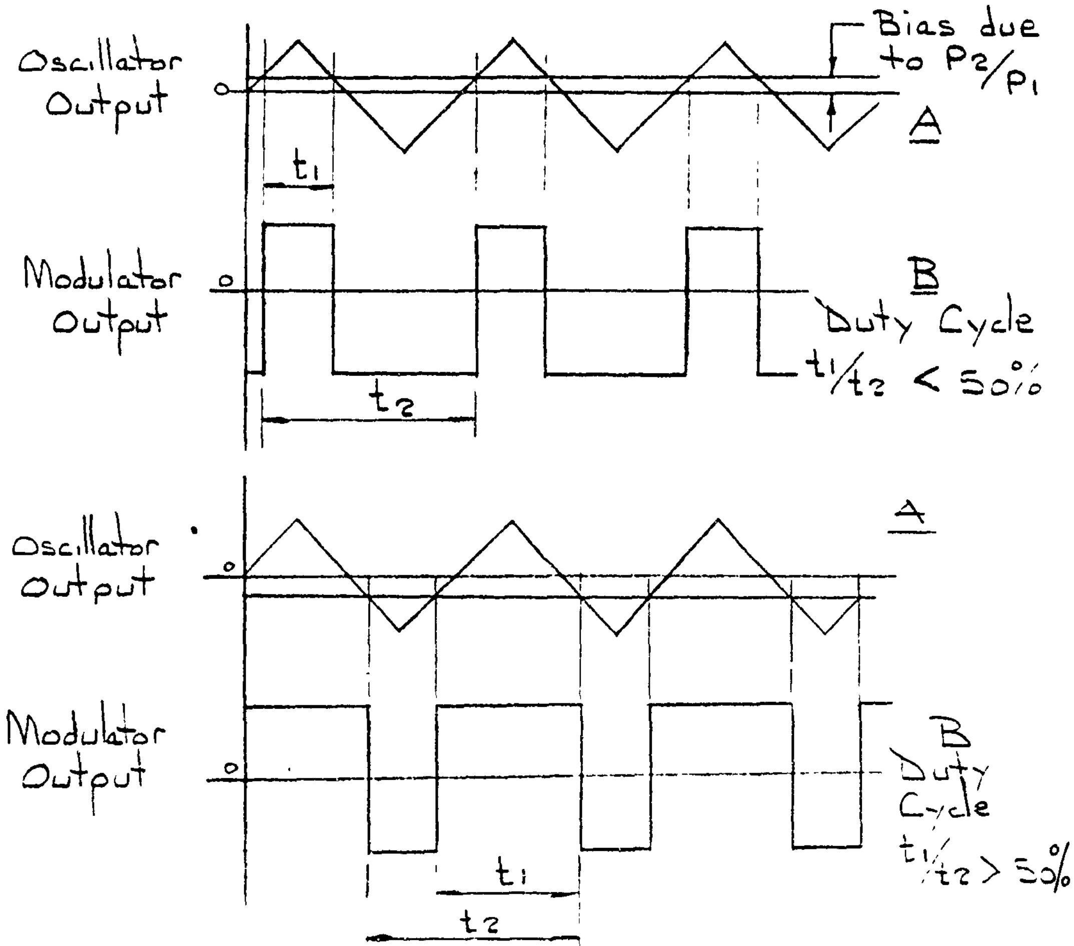


Fig 5 Effects of Pressure Ratio

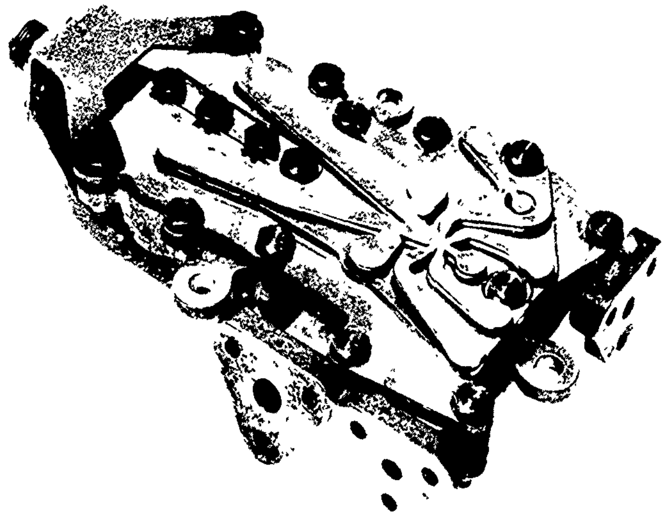


Fig 6a Modulator Side and Connector

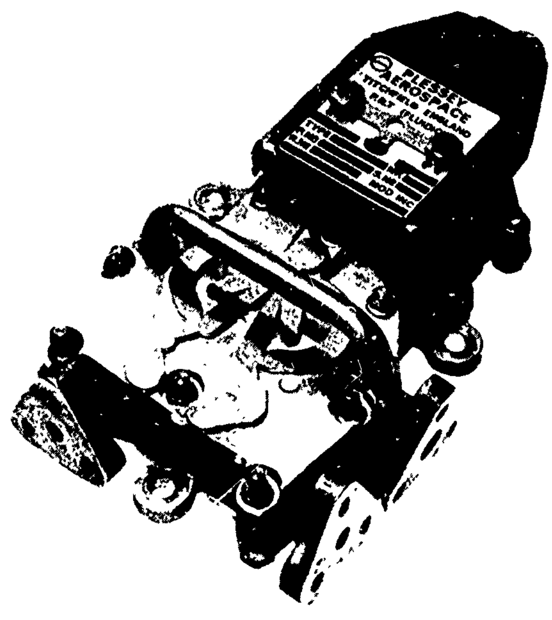


Fig 6b Oscillator Side

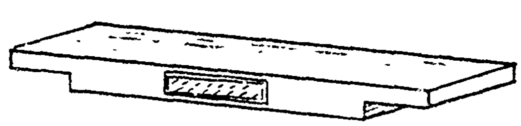


Fig 7 P.R.P.U.

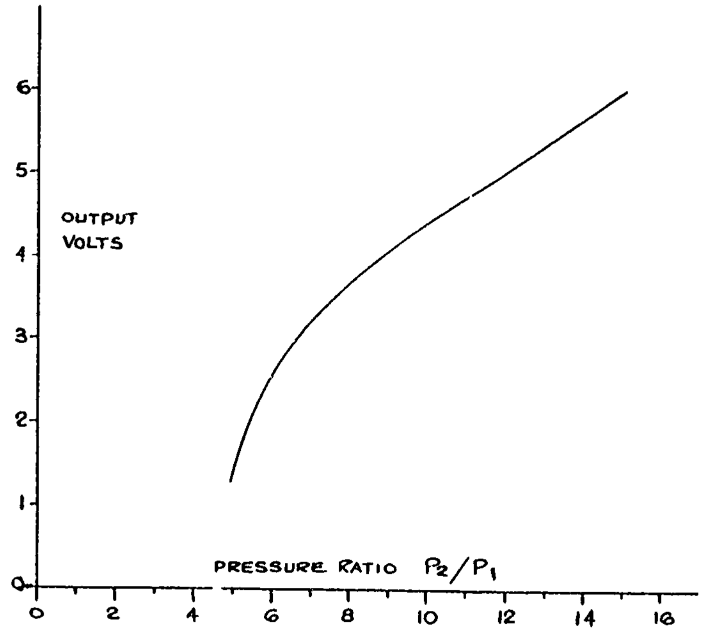


Fig 8, P.R.T. Calibration

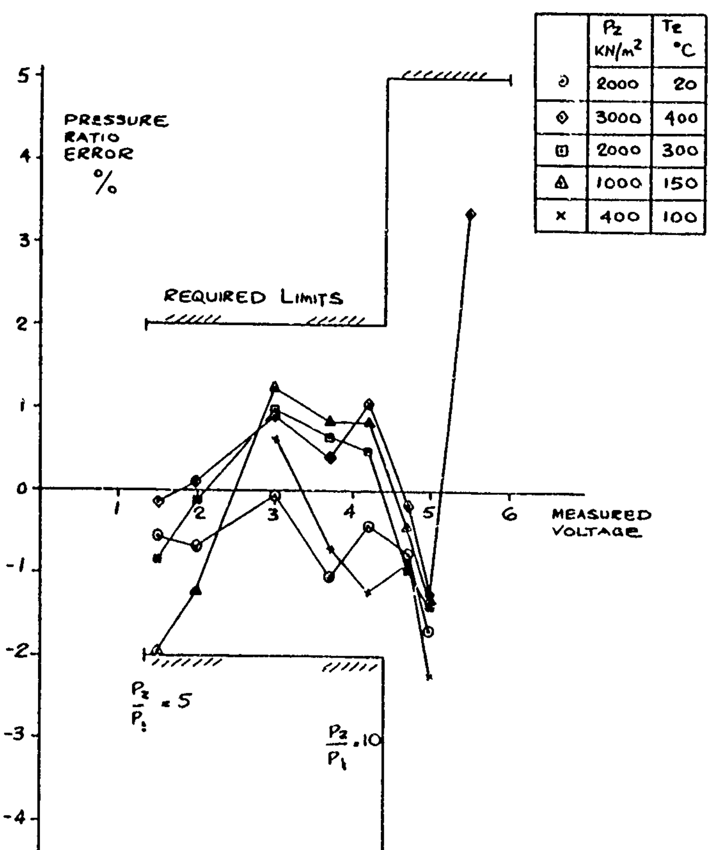
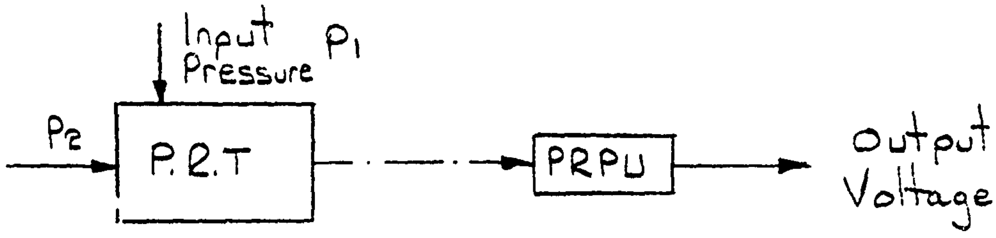
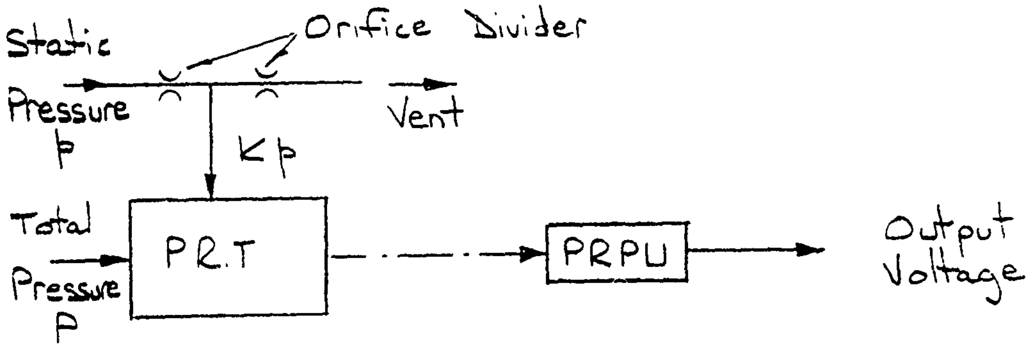


Fig 9, P.R.T. Accuracy Plot



A Pressure Ratio Measurement



'B' Normalised Mass Flow Measurement

Fig 10 Mass Flow Measurement using the PRT

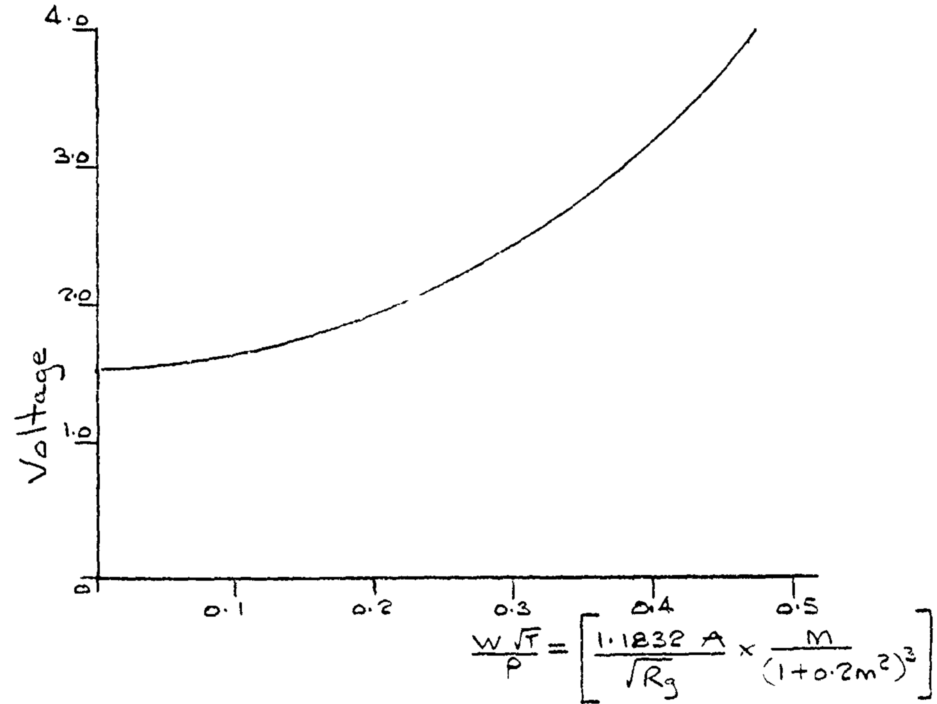


Fig 11 Mass Flow Transducer Calibration

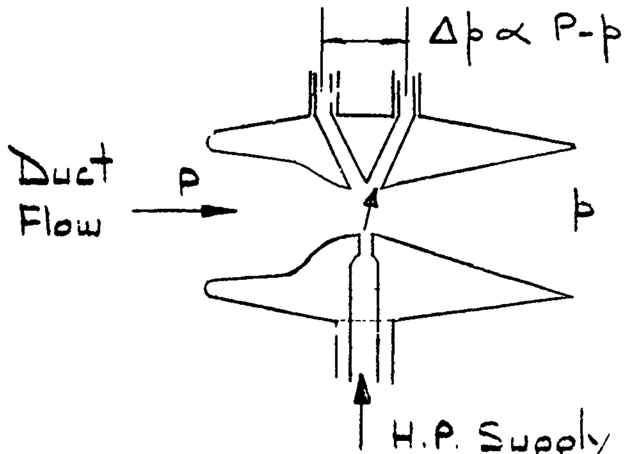


Fig 12. Low Pressure Duct Flow Measurement

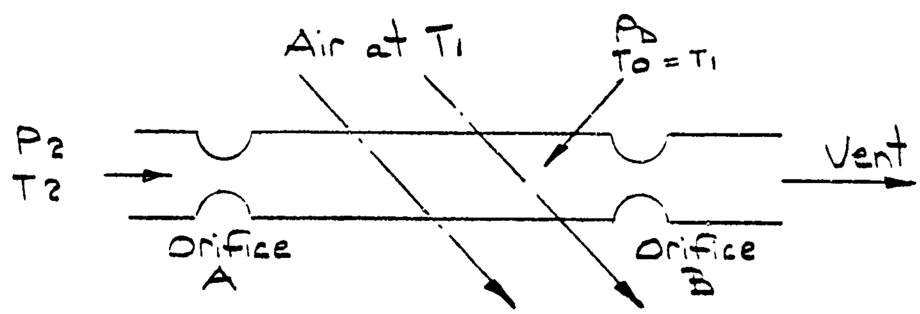


Fig 13. Temperature Ratio Sensing

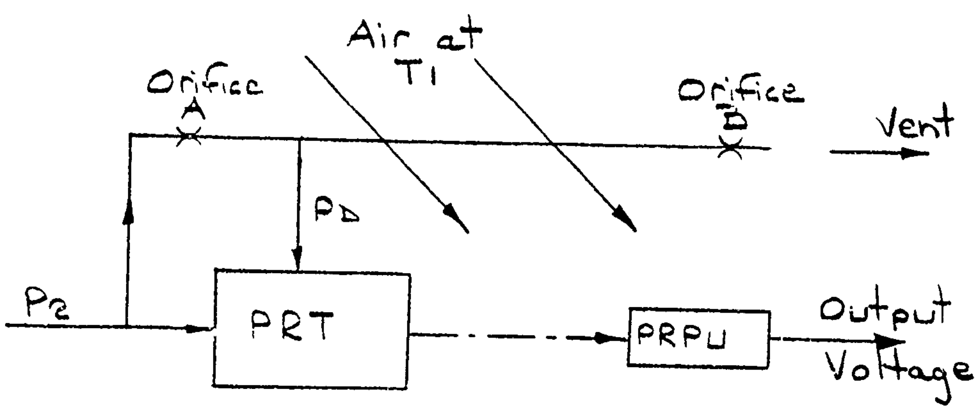


Fig 14 Temperature Ratio Measurement

DISCUSSION

David J.Hawes, Ca

Compared with conventional Parameters.

$N/\sqrt{T}$ easy to measure, $\sqrt{T}$ reduces effect of temperature inaccuracy

Pressure Ratio

Weight, cost and reliability comparison with "conventional" pressure ratio systems

Problems of changes in pressure profile over flight envelope

Author's Reply

I agree that $N/\sqrt{T_1}$ is easy to measure because intake temperature T_1 covers only a small range and does not change rapidly. However, this parameter does not provide all of the information about the core of a multispool engine For example, the important parameter relating to the HP spool in a 3 spool engine would be $N_H/\sqrt{T_3}$ where N_H is the HP spool speed and T_3 the HP intake temperature (or IP compressor discharge temperature).

The measurement of T_3 is much more difficult than T_1, particularly because the rate of change of T_3 may exceed 100°C/sec in a rapid acceleration. Because of this $N_H/\sqrt{T_1}$ is normally used, with consequent loss of information about the exact working condition of the HP spool. Pressure ratio, however, can be measured quite easily and it is therefore a simple matter to monitor the pressure ratio P_3/P_4 across the HP compressor.

Conventional pressure ratio sensors using bellows and levers are generally bulky and subject to failure in severe temperature and vibration environments.

Regarding the cost comparison I can only refer to a very early fluidic pressure ratio sensor with a hydro-mechanical interface This unit costs approximately 60% of the cost of the mechanical system it replaced. I have no other direct cost comparisons.

Regarding distortion of measurements over the flight envelope, this has been no problem.

P.Brammer, UK

With the described double orifice pressure ratio sensing device what is the necessary level of T_1 accuracy? Also what effect would air released in the intake from anti-icing system have on accuracy?

Author's Reply

You are, I presume, referring to the temperature ratio sensor The air in the duct between the two orifices would be cooled to the T_1 temperature. This would be ensured by allowing the jet from orifice A to blow on the inside walls of the duct to obtain good heat transfer, and also by having an adequate length of duct.

The use of an intake anti-icing system which heats the intake locally could of course change the sensed value of T_1, and thereby change the measurement of T_2/T_1 This however is a problem common to all systems where T_1 is measured, and must equally apply to the measurement of $N/\sqrt{T_1}$. I am not offering a solution to the problems associated with T_1 measurement, but simply offering a new parameter, T_2/T_1, if T_1 is available.

G.Serovy, US

Please clarify the answer to the question from Canada (concerning the effect on the pressure ratio indication of changes, distribution of compressor discharge pressure with operating point). Where in the annulus is the compressor exit pressure measured and with what type of sensor?

Author's Reply

In the particular application where we have flight experience we are not aware of any distortion problem affecting the pressure ratio transducer We do know however, that compressor discharge pressure was chosen by the engine manufacturer as one part of the pressure ratio function because this was not very susceptible to flow distortion

Fan pressure ratio was rejected because of this problem I can only assume that the rotating machinery between the intake and the compressor discharge tends to smooth out any distortion effects The pressure tapping point in the engine is a static pressure sensor on the outside of the discharge annulus, but I cannot be more specific than that

A COMBINED PARALLEL-DIGITAL AND PULSE-DURATION MODULATED FUEL METERING SYSTEM

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1. Summary

Control units for gas turbine engines in use today or in the future, work according to control algorithms which strive for the most accurate metering of the primary energy contained in the fuel. A fuel metering system is presented which can be controlled parallel-digitally by a computer. This system seems to be preferably suited for small and medium size engines. High accuracy requirements coupled with both robust and simple construction can be met. The design and functional description is supplemented by the laboratory test results so far achieved.

2. Introduction

The common electro-mechanical metering units, which are working on the principle of an analog or an incremental variation of a metering area are complex in comparison with the corresponding units used in purely mechanical controls. Close fits between piston and sleeve, as well as an accurate profile configuration of the metering area are still prevailing. In addition, the following extra components are provided:

- Electro-mechanical converters with torque motor or stepper motor to drive the sliding valve.
- Electro-mechanical feedback for the metering area, in which case dual redundancy or corresponding monitoring is desired.

With a similar metering principle applied and with the same exacting requirements with regard to functional control accuracy as required for a large engine, a lower rated engine would practically require a scaled-down version of such a metering unit. When disregarding the material expense, the cost would hardly be lower than that of the larger version, and the reliability would of course be inferior due to the miniaturisation of the mechanical components.

Due to this circumstance, other engineering solutions have to be found, in particular solutions which do not merely represent a scaled-down version.

3. Description of the Metering Principle

3.1 Metering by Means of On-Off Valves

For the purpose of controlling a mass flow in industrial process engineering, several on-off valves having different metering areas are connected in parallel.

All depending on the demanded flow rate, some of the valves may be kept open or closed. The metering areas are graded to the binary system. As may be seen from Fig 1, the difference between demanded and actual flow is 12.5% of the maximum value when using three valves only. This difference is unacceptably large. To reduce this difference to a value adequate to gas turbine engines nine valves equivalent to the resolution 512 would be required. The disadvantage of this arrangement may not only be seen in the large number of valves that is to say structural weight, cost, energy consumption, but also in the problem caused by the very small area of the valve having the lowest binary gradation.

Nevertheless, on-off valves offer inherent advantages compared with proportional valves:

- They have but two exactly defined flow values, e.g. zero and maximum.
- They do not require a displacement feedback.
- They are of a more simple design, considerably cheaper and much more reliable, so that also the application of several valves is acceptable.
- Their switching times are so short, that the dynamics of the metering operation are only dependent on the hydraulic conditions of the manifold system.

A different way of varying the metering area is shown in Fig. 2. The serrated line depicts the residual flow which in Fig. 1 is still missing to achieve a continuous metering characteristic. A valve is opened and closed at a constant sequence, with the opening time being changed at the expense of the closing time so that the total of the two times remains unchanged. This so-called pulse-duration modulated (PDM) controlling of a valve allows for a proportional timing of the mean time value of the fuel flow.
Fuel injection systems of motor vehicles are working in a similar way. It is, however, quite problematic to chop fuel flow rates of a magnitude as is required for gas turbine engines. Besides, the amount of electric energy required by such a valve, as well as the weight of the valve itself, would be disproportionally high. In addition, linear modulation of a solenoid valve can, in practice, only be achieved within a limited flow range. An explanation of these circumstances is given in Fig. 3: Due to its limited switching speed an on-offvalve requires a certain settling time (Ts) for safe opening and closing. Therefore, Ts has to be subtracted from one period T in order to reach the longest permissible effective opening time up to which a linear modulation of the valve is still possible. The shortest possible effective opening time is approximately equal to Ts. From this, one may calculate the metering range R as follows

$$R \approx \frac{T - Ts}{Ts}$$

High performance valves which, particularly for pulse-duration modulation, are provided with a fast switching property, have a settling time of Ts = 1 to 1,5 ms. At a modulation frequency of 50 Hz the remaining metering range would nevertheless be R = 12, whereas at 100 Hz the range would reduce to 5,6. But even a metering range of 12 is too narrow for a gas turbine engine, so that at this point pulse-duration modulation as a sole means of metering has found its natural limitation. Frequencies of much less than 50 Hz cannot be applied for reasons still to be explained (Refer to 5.1). It is in fact only by the combined employment of the two metering methods that the disadvantages inherent to each individual method may be largely eliminated (refer to Fig. 4).

In the example explained here, altogether four valves are used which, thanks to appropriate signal processing, are able to achieve a wide linear metering range with a satisfactory resolution capability. It may furthermore be seen from this example that a maximum flow of the cycle valve V1 must be higher than the flow of the lowest binary graded valve V2 due to the limited modulation range (chosen R = 6). In this case the difference is 2.5% of full scale and the values of both coordinates has increased by that amount.

3.2 Signal Processing

Fig. 5 shows the simplified circuitry of a metering system design having four on-off solenoid valves, V1 through V4, connected in parallel. The pressure differential ΔP across the valves is kept constant by a pressure control of the usual design. The input signal Qdemand is coming from the engine control system and is converted into the fuel flow Qact to the burner as follows: The binary coded analog-digital converter forms the control signals U2, U3, U4 for the basic flow valves V2, V3, V4. The electric analog flow values Q1 through Q4 of the individual valves are stored in a calibration device by means of four potentiometers. Independent of the signal levels (either high or low level) U1 through U4, the switch unit transfers the calibrated flow values Q1 through Q4 of the opened valves to the summation point (feedback). Therefore, the signal Qact.electr. represents the electrical analogy of the fuel flow. Manufacturing tolerances affecting the flow rates of the valves may, within certain limits, be compensated by the electrical calibration device. The difference Qdemand minus Qact.electr. acts on an integrator which, in turn, controls a pulse-duration modulation circuit supplying the control pulses for the cycle valve V1.

The analog-digital converter must, in addition, generate switching hysteresises H (Fig. 4) to prevent a slight unsteadiness in the desired value, i.e. around point A, from causing an uninterrupted switch-over of the basic flow valves V2, V3, V4. The hysteresis is in the order of a few percent and is taken into account by the pulse-duration modulated valve V1 due to its modulation reserves.

Fig. 6 illustrates valve position and the course of control voltage Uc at steps of Qdemand based on the above mentioned valve flow gradation. At Qdemand of 18%, 12.5% of the full scale flow rate are metered by valve V2. The control voltage Uc, the intersections of which with the auxiliary delta voltage Ud are generating the control pulses for valve V1, changes until the mean time value of the flow from V1 corresponds with the remaining 5.5%.

At a small input step of the demanded value to, i.e. 21%, only the modulation ratio will be changing, whereas at a big input step to e.g. 89% also the basic flow valves will be switched on.

The rate of the integrator is chosen such, that in the extreme case, when valve 1 is fully opened or fully closed, the trace of Ur will be flattened a little more than that of Ud, since otherwise there would be several intersections within one period, which would cause undesired additional cycles. With the regulator adjusted in such a way, each desired flow value may be electrically set within one cycle period.

4. Hydromechanical Part

A schematic diagramme of the hydromechanical part of the metering unit is shown in Fig. 7. At this design configuration, the solenoid valves V1 (pulse-duration modulated) and V2 (binary) are directly metering part of the fuel flow, whereas valves V3 and V4 (binary) are servo-flow actuated by one magnetic pilot valve each. The effective direction of all valves has been chosen so that they open when being energized. The servo pressure differential P2-P4 across the pilot valves is controlled in such a way that it may be kept constant to values which are compatible with the valves. ($P4 \approx P2-2\ \Delta P$). During the switching operations the servo flow is employed for a short duration of time only, since at opened pilot valves the pertaining balls are contacting the left-hand stops, thereby excerting a sealing action. When closing the pilot valves, the balls occupy their respective valve seat at their right-hand side. During this sequence fuel passes through the annular gaps between ball and guiding sleeve into the chamber arranged at the left-hand side of the ball.

The solenoid valve of this first breadboard unit originates from an automotive injection system and has been modified for the present application.

5. Functional Behaviour, some Data

5.1 Flow Pulsations and Metering Range

In Fig. 8 the relative share r of the pulsating flow is plotted versus the mean flow Qm, on the basis of the four-valve-arrangement.

The particular trace of the curve may be accounted for by the superposition of two effects. At the relative maximums of the pulsations, that means, at the points where the largest absolute flow change ΔQ occurs, a modulation ratio of 1:1 (50% modulation) is prevailing. Above or below that modulation ratio, the absolute flow change deminishes. In conformity with the definition of r the pulsations at lower flows are higher rated accordingly, so that a hyperbolic function is created.

As may furthermore be seen from Fig. 8, the pulsations are dependent on the relation between the hydraulic time constant of the metering unit and the cycle duration T of the modulation frequency. The hydraulic time constant is primarily determined by the storage volume of a piston or a diaphragm in the pressure differential control, but also by the diameter and the length of the burner line and by the flowcharacteristic of the burner. The pulsations are measured directly at the burner. Since pressure differential controls fitted with metering units, as used for small gas turbine application are, in particular, operating without servo energy, they require diaphragms (or pistons) which have a relatively high stroke volume. This means first of all that irrespective of the design of the metering unit employed, the time constant τ for the step response of the fuel flow may hardly be expected to be less than 80ms. This also applies to the described case. When choosing a modulation frequency of 50 Hz (T = 20ms), τ/T will be 4.

It may be seen, that at 5% of maximum mean flow Qm, 9% of the flow pulsations are still prevailing which are causing a corresponding fluctuation of the flame temperature in the combustion chamber. Relevant investigations have still to be undertaken. It can be said already now that the temperature at the surface of the turbine blades will only be affected by a small residual amount of the pulsations. As a result of the pneumatic storage capacity of the combustion chamber and of part of the compressor, the pressure pulsations to be expected will be additionally smoothed. Besides, the load limit of gas turbine engine is not reached at 5% of the maximum flow. In most cases the total metering range of small to medium size gas turbine engines does not exceed 20.
The pulsating share may also be reduced by providing for a fixed minimum flow by-pass of e.g. 2.5% (refer to broken line of curve). In this case a certain disadvantage may, however, be seen in the circumstance that in the lower part of the flow range the pulse-duration modulated valve would have to be continuously modulated down to zero flow, which would entail a linearity loss. This may be avoided by starting the metering range only above 5% of Qm.

A further possibility to reduce the pulsations at low flows would be to modulate in the push-pull mode valves 1 and 2 at less than 15% of Qm.

This would cut the cycle duration to 10 ms, so that in this case the more favourable dotted curve would apply for $\tau/T = 8$. If the original linearity shall be maintained, the metering range has to be reduced, since the total of the lowest permissible flows of valves 1 and 2 are now determining the minimum flow of the metering unit.

The additional pulsations which occur when switching on the basic flow valves are negligibly low. The total switching time of the ball valves plus pilot valves is in the order of 3 to 4 ms. The dissymmetry of the switching behaviour does not exceed 1 ms. If e.g. valve V4 is in the fully opened position 1 ms later than V3 or V2 have switched to the closed position, the flow would drop to the zero flow rate (refer to Fig. 4, e.g. Point A) for a duration of 1 ms, disregarding the hydraulic inertia. With due regard to the time constants of the fuel lines and to the storage volume of the pressure differential control, it can be said that the actual flow drop is in the order of 1%.

5.2 Accuracy

With four valves employed, the linearity deviation is less than ± 2% of reading over a flow range of 80:1. At the beginning of the investigations, type and temperature of the fuels were kept constant. For the rest, the same problems with regard to viscosity and density are present than are experienced at the common continuous metering systems.

In both cases the accuracy is in addition, influenced by the quality of the pressure differential control. Simple controls are keeping the pressure differential constant within ± 4 to 5%. The effect of this deviation on the flow rate being approximately half of that percentage. During the investigations so far performed, the deviation of the pressure differential control was eliminated in order to be able to determine the accuracy which originates alone from the behaviour of the on-off valves.

5.3 Consumption of Electrical Power

On principle, fast acting on-off valves require a comparatively high controlling power. By appropriate measures, only a short-time current peak is applied to the valve, whereas but a low current is required to keep the basic flow valves open. The mean power consumption of the four valves is altogether 15Watt with the controlling electronics included. This value still remains within reasonable limits at a maximum flow rate of nearly 300 kg/hour.

6. Conclusion

According to the first investigation results obtained on a breadboard metering unit, the accuracy which on present metering systems can only be achieved by employing a sophisticated feedback, can now apparently be reached with more simple means. The combination of pulse-duration modulated valves and binary graded valves does, however, cause residual flow pulsations.

To obtain detailed knowledge on the affect of such pulsations, relevant combustion chamber and engine tests have still to be undertaken. The described method of controlling the valves is, in the first instance, suitable for analog flow values and has proved to be successful for basic investigations.

It is also intended to control the valves directly by a digital computer.

Even if no weight reduction is expected from the described metering unit it can nevertheless be said that the production cost will be lower thanks to the more simple design. An improved reliability is also to be expected.

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8. Acknowledgement:

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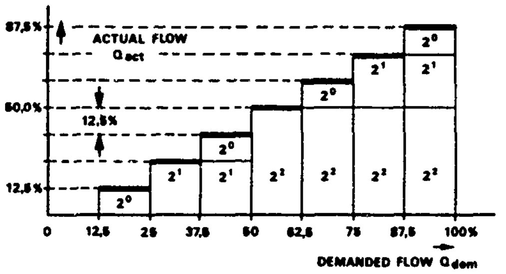

Fig. 1: BINARY STEPPED FLOW

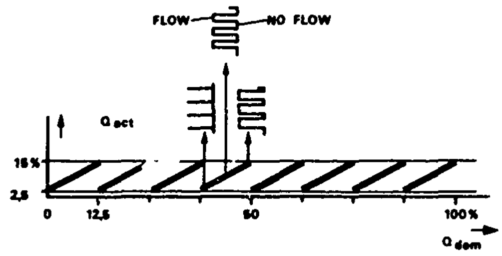

Fig. 2: FDM FLOW

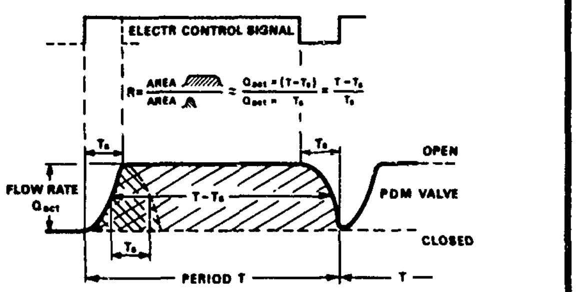

Fig. 3: PDM LINEAR METERING RANGE R

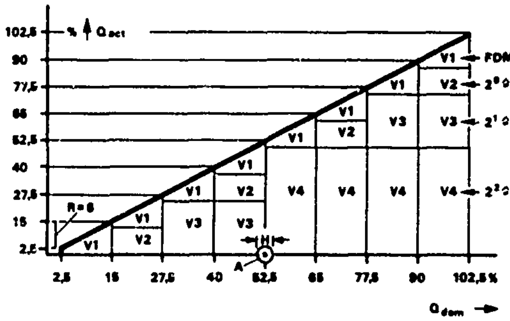

Fig. 4: COMBINATED PDM and BINARY FLOW

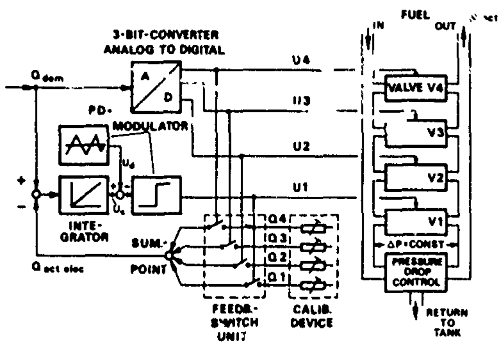

Fig. 5 VALVE CONTROL CIRCUITRY (PRINCIPLE)

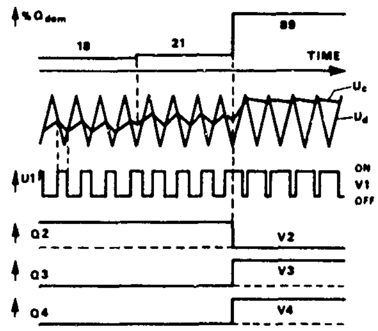

Fig 6. VALVE POSITION and U_c-RESPONSE due to INPUT STEPS

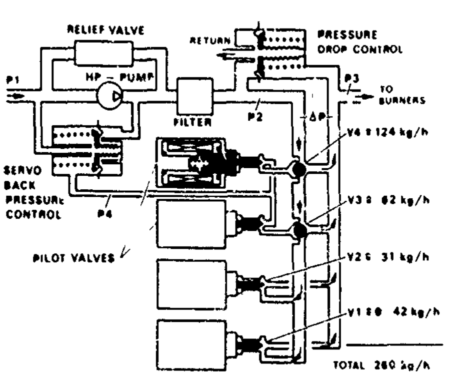

Fig. 7: BREADBOARD FUEL METERING SYSTEM SCHEMATIC

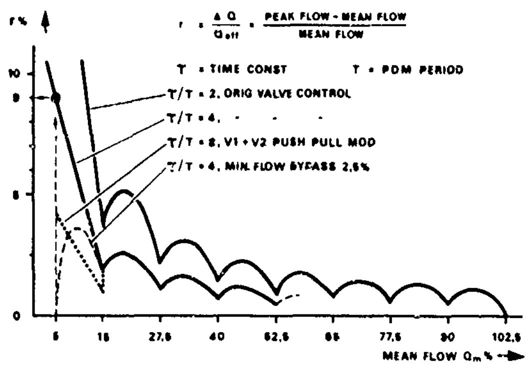

Fig 8 RIPPLE FACTOR VS MEAN FLOW

DISCUSSION

D.M.Griffiths, UK

What is the perturbation in fuel flow when V4, which switches one half the total flow, changes state?

Author's Reply

(a) If for instance V4 is closed, valve V2 and V3 will simultaneously open. The degree of modulation of V1 will change also (refer to Point A in Figure 4). It is in particular due to the special kind of control employed that large perturbations, as are for instance still occurring in Figure 1, will be avoided.

(b) Though perturbations are still present during the transient time, they are only in the order of 1%, since the transient time takes just a few milliseconds (approx. 4–6 ms at V3 and V4, and approximately 1.5 ms at V2 and V3), and since the flow spikes are intensely smoothed due to the hydraulic inertia of the fuel manifold

M.J.Joby, UK

The smallest valve in the system in required to oscillate rapidly what life can be expected with this device, and are dirt and magnetic debris likely to cause problems?

Author's Reply

During the breadboard tests carried out so far, Bosch solenoid valves (for fuel injection on Otto engines) have been used for V1 and V2, and pilot valves have been used for V3 and V4.

Irrespective of the poor lubricating properties of gasoline, such valves (refer to Figure 7) have not shown any wear, not even after 150,000 driven kilometers (approx. 3 000 hours). The valves are provided with strainers to keep away dirt and metal particles which have passed through the working filter fitted at a further upstream location Magnetic debris having a particle size of $<10 \mu m$ does not accumulate in the valves used. This may obviously be attributed to the frequent and abrupt armature movements, to the fact that the valves are flushed with fuel and last but not least, to the vibration imposed from the outside (in the case of the Otto engine) For the rest, it is also conceivable that minute particles, as far as they are not stainless, are developing a lubricating property in conjunction with the fuel Gas turbine application design techniques may also be applied, which lead to an increased reliability, such as for instance the frictionless suspension of the magnet armature by means of so called spiders.

APPLICATION DES MICROPROCESSEURS A LA REGULATION DES MOTEURS D'AVIONS MILITAIRES
Conception des régulateurs électroniques

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RESUME

La disponibilité de circuits à haut niveau d'intégration offre au concepteur de nouvelles possibilités pour définir rationnellement des automates numériques intégrés dans le système de régulation des propulseurs.

L'architecture de ces automates est définie en prenant simultanément en compte :

- les spécifications fonctionnelles,
- les spécifications opérationnelles qui portent notamment sur la fiabilité et sur la sécurité des missions,
- les contraintes technologiques imposées par un environnement agressif.

1. - INTRODUCTION

Les performances toujours plus grandes exigées des turboréacteurs -poids, poussée, consommation, pilotabilité, sécurité, disponibilité- dans de très vastes domaines de vol impliquent une sophistication sans cesse croissante de leur système de régulation. Dès lors, les motoristes sont conduits à associer des régulateurs hydromécaniques et électroniques en répartissant l'autorité relative de ces deux techniques en fonction des objectifs à atteindre, qu'ils soient fonctionnels, opérationnels ou économiques.

L'évolution spectaculaire de la densité des circuits intégrés permet de disposer de micro-mini-calculateurs dans un boîtier de 10 cm^3 ou de réaliser des unités de traitement à très hautes performances en associant une douzaine de circuits LSI. Dans ces conditions, nous pouvons réaliser des régulateurs utilisant au mieux les ressources matérielles et logicielles.

L'analyse du processus de régulation, la définition claire des objectifs de sûreté de fonctionnement, la prise en compte des contraintes imposées par l'environnement permettent au concepteur de définir méthodiquement des structures particulièrement adaptées à la régulation des turbomachines.

2. - DÉFINITION DES STRUCTURES FONCTIONNELLES D'UN RÉGULATEUR NUMÉRIQUE

2.1. - ANALYSE DES SPECIFICATIONS FONCTIONNELLES

Les spécifications fonctionnelles portent sur :

- l'acquisition des paramètres de la régulation,
- l'exécution des tâches correspondant aux différentes phases de la régulation,
- l'actuation,
- le comportement dynamique.

2.1.1. - Acquisition des paramètres de la régulation

Le nombre de paramètres à acquérir dépend des lois de régulation et des niveaux de redondance retenus. Une configuration typique est donnée figure 1.

Le choix des capteurs adaptés à un traitement numérique est relativement limité compte tenu des contraintes de fiabilité (environnement physique), de sécurité (testabilité) et de facilité d'isolement galvanique.

2.1.1.1. - Mesures de position

Les capteurs électromagnétiques, fonctionnant en ratiomètre avec des fréquences porteuses comprises entre 400 et 4000 c/s, sont bien adaptés aux problèmes posés.

En fonction du nombre de capteurs et des bandes passantes nécessaires, nous utilisons trois modes de traitement :

- l'approche classique de la figure 2.1. avec un module de conditionnement par voie,
- l'échantillonnage direct du signal alternatif associé à un circuit de calcul et de filtrage (figure 2.2.),
- le multiplexage d'un démodulateur (figure 2.3.) en effectuant l'acquisition en parallèle avec le calcul et en compensant l'effet des retards par des réseaux correcteurs appropriés.

2.1.1.2. - Mesures de vitesse de rotation

La vitesse de rotation est représentée par une fréquence délivrée soit par des capteurs inductifs soit par des alternateurs. La mesure des états successifs d'un compteur et d'un filtrage numérique permet d'échapper au compromis périodemètre-fréquencemètre.

2.1.1.3. - Autres informations

L'acquisition de signaux continus se ramène au cas du paragraphe 2.1.1.2. par la mise en place de modulateurs flottants. L'isolement des signaux [illegible] est assuré par des coupleurs [illegible] ou des transformateurs.

2.1.2. - Actuation

L'élaboration des signaux de commande (6 à 8 commandes continues, 8 à 10 commandes tout ou rien) ne pose pas de problème de choix si nous nous imposons l'une des conditions suivantes :

- maintien des sorties à la valeur précédente en cas de panne autodétectée,
- commutation à une valeur prédéterminée par une commande pilote.

2.1.3. - Les tâches correspondant aux différentes phases de la régulation

2.1.3.1. - Représentation du fonctionnement

Une propriété fondamentale du processus de régulation est que l'état du moteur dépend essentiellement de l'état précédent et que les transitions possibles entre états sont en nombre fini et bien déterminé (figure 3).

La prise en compte de la répétition des phases de régulation sec et/ou post-combustion à chaque période d'échantillonnage et de leurs spécifications particulières permet de compléter le réseau initial et d'obtenir l'organigramme général de la figure 4.

Chacune des transitions du graphe de la figure 3 peut être représentée par des graphes partiels qui conduiront à des organigrammes détaillés : à titre d'exemple, le fonctionnement de la phase d'allumage de la post-combustion est décrit par les figures 5.1., 5.2. et 5.3.

La modélisation par réseaux de Pétri du fonctionnement général du système puis l'établissement et le regroupement de réseaux partiels facilitent le dialogue entre les ingénieurs concernés par la régulation, qu'ils soient thermodynamiciens ou électroniciens, permettent de détecter les oublis et de lever les ambiguïtés des spécifications, conduisent sans difficulté à l'établissement des organigrammes. Par ailleurs, cette modélisation peut rendre systématique l'extraction du parallélisme entre les différentes tâches de la régulation (BEO 77).

2.1.3.2. - Charge de calcul

L'ensemble des calculs à effectuer à chaque période d'échantillonnage représente une charge équivalente à l'exécution de 500 à 2000 opérations élémentaires de mémoire à mémoire.

Cependant, l'analyse des interactions entre les différentes boucles et l'indépendance de certaines fonctions à l'intérieur des boucles, permet de dégager un degré de parallélisme important, ce qui permet d'envisager l'utilisation de plusieurs processeurs banalisés ou spécialisés pour constituer l'unité de traitement.

2.1.4. - Comportement dynamique

La précision et la stabilité de la boucle de régulation sont liées au choix de la période d'échantillonnage.

Nous avons retenu pour un régulateur électronique à hautes performances une période d'échantillonnage de 20 ms avec la possibilité d'affecter à des tâches déterminées un nombre de périodes multiple ou plus rarement sous-multiple de la période de base.

2.2. - PRISE EN COMPTE DES CONTRAINTES TECHNOLOGIQUES

L'automate de régulation numérique doit assurer les performances requises dans un environnement thermique, vib[illegible], électrique et radio-électrique particulièrement sévère qui limite les choix des technologies L[illegible].

La technologie bipolaire (TTLLS) autorise de très bonnes performances, sa fiabilité prévisionnelle est la plus prometteuse. En contrepartie, elle demande un refroidissement plus efficace, et le problème des microcoupures d'alimentation ne peut être résolu qu'en faisant appel à des sous-ensembles CMOS.

La technologie CMOS, lorsque les performances sont suffisantes, semble particulièrement bien adaptée aux applications militaires. L'immunité au bruit est excellente, son évolution en température est stable, sa consommation statique est faible.

Nous avons éliminé la technologie I^2L pour cause d'immaturité et les technologies MOS dynamiques qui se sont révélées trop sensibles à haute température.

Nos applications actuelles sont donc basées sur les microprocesseurs :

- *2900* : Microprocesseur en tranche de 4 bits, microprogrammable.
  La famille 2900 est très largement utilisée dans des applications militaires et spatiales. Les versions actuelles sont en technologie bipolaire mais de nombreux constructeurs développent des versions CMOS sur saphir dans le but de réduire les consommations et d'étendre le fonctionnement à des temperatures très élevées.

- *6100* : Microprocesseur 12 bits en technologie CMOS.
  Le logiciel du 6100 est compatible avec celui du calculateur PDP8F.

- *1802* : Microprocesseur 8 bits en CMOS.
  L'architecture du COP 1802 rend particulièrement aisée la manipulation de données.

2.3. - CHOIX DES STRUCTURES FONCTIONNELLES

Le régulateur électronique assure deux fonctions essentielles :

- le séquencement de la régulation tant au niveau global qu'au niveau de l'exécution des tâches élémentaires (figures 3 et 4),
- le traitement des fonctions arithmétiques associées.

Les fonctions de séquencement et de traitement peuvent être regroupées, on a alors une structure classique de mini-calculateur géré par un moniteur temps réel, ou partagée physiquement entre un opérateur de commande et des opérateurs banalisés ou spécifiques.

Le choix entre ces structures est lié aux spécifications générales de l'application envisagée : capacité de traitement évolutive ou non, facilité d'introduction des techniques de sûreté de fonctionnement, adaptation à l'évolution de la technologie...

Les possibilités offertes par les microprocesseurs en vue de la réalisation de régulateurs électroniques sont illustrées par la description sommaire de trois ensembles :

1. un régulateur électronique type mini-calculateur (figure 6.1.)
2. un système multi-microprocesseur (figure 6.2.)
3. un régulateur à opérateurs (figure 6.3.)

2.3.1. - Un régulateur électronique du type mini-calculateur

Ce régulateur est organisé en associant à un microprocesseur CMOS un opérateur arithmétique. Il comprend deux cartes :

1. La carte interface analogique qui assure les conversions analogiques-numériques et numériques analogiques ainsi que la mise en forme des signaux tout ou rien. Pour obtenir une configuration matérielle minimale, les voies d'entrée et de sortie sont transférées par l'intermédiaire de buffers considérés comme des adresses mémoire.

2. La carte processeur (figure 7) est constituée par :

- un microprocesseur COSMAC (8 bits),
- un multiplieur 16 bits du type série-parallèle réalisé en micro-électronique hybride,
- une mémoire programme de 4 k octets,
- une mémoire de travail de 1 k octet.

Ce processeur est capable d'exécuter en 5 ms environ l'ensemble des traitements d'un correcteur numérique simple réalisant :

- l'acquisition de 4 voies analogiques,
- le calcul de 3 générateurs de fonction,
- la commande de 2 boucles de courant en mode proportionnel et intégral,
- la commande de 3 voies analogiques et de 5 voies tout ou rien.

L'exécution du programme est contrôlée par un micro-moniteur ce qui permet de programmer les différentes tâches de la régulation comme des blocs indépendants et d'effectuer périodiquement des tests de bon fonctionnement (autotest à la mise sous tension, calcul de vraisemblance...).

2.3.2. - Un régulateur multi-processeur

Un régulateur constitué par un ensemble d'unités fonctionnelles banalisées capables d'exécuter plusieurs traitements simultanés est particulièrement attractif. Une telle structure permet en effet :

- l'augmentation progressive de la capacité de traitement,
- la reconfiguration du système en cas de panne détectée,
- la standardisation de sous-ensembles réalisés avec des micro-calculateurs fiables et relativement peu onéreux.

Par ailleurs, le contrôle réciproque des diverses unités améliore l'efficacité des autotests.

La modélisation du processus de régulation par réseau de Pétri et l'utilisation des programmes d'ordonnancement permettent de mettre en evidence le degré de parallélisme et d'utiliser au mieux les ressources disponibles.

Appliquée à la régulation en mode post-combustion d'un turboréacteur simple corps double flux, on obtient les gains de temps d'exécution représentés figure 8.

L'organisation présentée figure 9 conduit à des taux d'occupation de 70 %, 85 %, 56 %, 63 % de chacun des 4 processeurs.

En fonction des critères représentés figure 10, nous avons retenu pour un système de régulation complexe la configuration suivante :

- contrôle centralisé par processeur maître,
- communications indirectes datées,
- bus commun.

Le processeur maître est chargé de gérer tous les échanges interprocesseurs et de reconfigurer les modules esclaves en cas de panne ; il est équipé d'une horloge temps réel.

Le nombre de liaisons de synchronisation entre les processeurs étant assez faible, les communications entre esclaves transitent par le maître qui peut alors les vérifier.

Le comportement du processus et le temps requis pour l'exécution d'une tâche sont parfaitement déterminés (organisation statique du système et instructions à temps constant). Dans ces conditions, l'allocation du bus est faite par le maître à des instants précis, ce qui permet un contrôle supplémentaire et rend facile l'établissement des protocoles de communication.

La mise en oeuvre d'une maquette de démonstration n'a pas posé de problème particulier. La configuration matérielle de l'ensemble de traitement est relativement réduite : 4 microprocesseurs, 49 boîtiers 24 broches, 56 boîtiers 16 broches.

2.3.3. - Un régulateur à opérateurs

ASMARA (Automate Sûr et Modulaire Adapté aux Régulations Avioniques) a été développé par le LAAS* dans le cadre des contrats DRME/ELECMA** et ELECMA/LAAS.

Sa structure est définie par affinements successifs en prenant en compte simultanément ou séquentiellement les contraintes et les objectifs :

- évolution vers un régulateur à pleine autorité, ce qui implique la capacité d'introduction des techniques d'obtention de la sûreté de fonctionnement,
- consommation faible à bas régime moteur de façon à assurer la régulation du rallumage en vol dans une configuration où la génération électrique autonome a une puissance limitée,
- fonctionnement à performances réduites en mode secours,
- grande capacité de traitement,
- faible dissipation thermique de façon à limiter le dimensionnement de la source de refroidissement de l'automate monté sur moteur,
- tolérance aux microcoupures de l'alimentation.

Il en résulte le schéma synoptique de la figure 11.

Le bloc de commande a une structure monoprocesseur réalisée autour d'un microprocesseur CMOS IM 6100 à faible consommation. Sa capacité de traitement est suffisante pour assurer le séquencement de la régulation complète et le traitement des modes rallumage vol et secours électronique.

Le bloc de calcul comprend un processeur 16 bits et une mémoire programme. L'utilisation d'un microprocesseur bipolaire en tranches fonctionnant avec un cycle d'horloge de 250 ns d'une part, le gain spectaculaire obtenu par les techniques de microprogrammation d'autre part, le rendent particulièrement performant. Notons qu'un champ du microséquenceur est réservé à la commande d'un multiplieur rapide ce qui permettrait si nécessaire de ramener le temps d'exécution d'une multiplication à 2 µs.

La mise hors tension du bloc de calcul pendant environ les 3/4 de la période d'échantillonnage, sous contrôle du bloc de commande, permet de limiter la dissipation thermique à 8 W.

La mémoire de sauvetage. L'énergie stockée dans un condensateur de 100 µF est suffisante pour sauvegarder pendant 100 ms, en cas de coupure d'alimentation, le contenu d'une mémoire CMOS en mode inactif. Cependant, les opérations de sauvetage étant toujours périlleuses, la mémoire est scindée en deux blocs aux rôles symétriques : un bloc contient les informations relatives à la période d'échantillonnage précédente, l'autre bloc permet de mémoriser les informations élaborées pendant la période en cours. Les rôles de chacun de ces blocs sont intervertis sous contrôle du séquenceur.

Les blocs d'acquisition et d'actuation ont un fonctionnement autonome sous contrôle d'un microprocesseur local chargé notamment de régler les conflits d'accès.

Les liaisons. L'utilisation de liaisons du type série parallèle permet de réduire l'interconnexion et de faciliter l'introduction des techniques de sûreté de fonctionnement.

2.4. - L'ORGANISATION LOGICIELLE D'UN REGULATEUR

Le comportement déterministe du moteur vis-à-vis de sa régulation permet de mettre en oeuvre un logiciel sûr de par sa simplicité et son observabilité.

2.4.1. - Le moniteur temps réel

Le nombre d'états et de transitions entre ces états étant parfaitement déterminé, l'enchaînement des tâches est du type statique : lecture de tables correspondant à la configuration du système et à l'état de l'horloge temps réel.

La structure générale représentée figure 12 fait apparaître trois groupes de fonctions qui ont la même organisation :

- le groupe de gestion des ressources matérielles A,
- le groupe régulation du processus R,
- le groupe développement D.

Les groupes A et R fonctionnent en temps réel, leurs interactions se bornent à des transferts d'arguments. Le groupe D permet à l'opérateur d'intervenir en phase de développement sur les groupes A et R. Son fonctionnement en temps réel n'est pas autorisé pour des raisons de sécurité.

* Laboratoire d'Automatique et d'Analyse des Systèmes

** Commande de processus à base de microprocesseurs et de circuits logiques à haut niveau d'intégration. Contrat DRME N° 74/431

2.4.2. - Le jeu d'instructions

Les techniques de microprogrammation permettent de créer un jeu d'instructions spécialisées particulièrement simple et efficace qui utilise au mieux la rapidité des microprocesseurs bipolaires et qui peut être mis en oeuvre sans faire appel à des spécialistes informaticiens :

- la structure multi-adresse facilite l'écriture, l'assemblage et la vérification des programmes de régulation, elle correspond par ailleurs au mode de pensée naturel de l'automaticien (d'autant plus que toutes les instructions du groupe R sont à adressage direct),
- le choix d'un répertoire spécialisé implanté par microprogrammation conduit à une réduction notable du temps d'exécution d'une tâche puisque l'enchaînement des microcommandes est du type explicite.

Des extraits du jeu d'instructions de l'automate ELECMA RN 1287 et un exemple d'application sont donnés figures 13 et 14. Dans le cas où l'application ne justifie pas l'utilisation de microprocesseurs microprogrammables nous remplaçons les instructions spécialisées par des macro-instructions.

2.4.3. - Représentation des données

Les variables réelles ayant une signification physique donc une dynamique bornée, nous avons choisi de les représenter en complément à 2 avec un cadrage en virgule fixe.

L'effet des troncatures dans les multiplications lorsqu'il dégrade la précision est compensé par des recadrages ; les dépassements intermédiaires, dans le cas d'accumulations, sont facilement détectés et corrigés.

3. - LES STRUCTURES OPÉRATIONNELLES

Les structures opérationnelles prennent en compte la sûreté de fonctionnement du système de régulation spécifiée en termes de fiabilité, de sécurité, de disponibilité.

3.1. - COMPOSANTES DE LA SURETE DE FONCTIONNEMENT

Le système peut se trouver dans les états suivants :

1) non défaillant
2) défaillant mais en panne détectée
3) défaillant en panne non détectée

la fiabilité (R) est la probabilité de se trouver dans l'état 1 de 0 à t.

la sécurité (S) correspond aux états 1 et 2 avec dans le dernier cas le maintien des grandeurs de commande à une valeur prédéterminée.

la disponibilité peut être mesurée par le MTBF.

la maintenabilité est liée à la probabilité de localisation et de réparation correcte des éléments défaillants.

3.2. - EVALUATION DES COMPOSANTES DE LA SURETE DE FONCTIONNEMENT

Les outils mathématiques issus de la théorie des processus stochastiques permettent un accès systématique aux composants de la sûreté de fonctionnement. Une analyse détaillée ainsi que de nombreux exemples de structures embarquées soumises à des cycles de mission, de vérification, de garage sont donnés par (LAP 75).

Les figures 15 et 16 montrent la nécessité d'une évaluation rigoureuse :

- les gains spectaculaires basés sur des hypothèses simplistes sont souvent illusoires,
- il est facile d'augmenter les coûts, le volume sans gagner sur la fiabilité.

3.3. - TECHNIQUES DE DETECTION ET DE RECOUVREMENT DES PANNES

3.3.1. - Les structures redondantes conduisent à un volume matériel important. L'évaluation de leur fiabilité et de leur sécurité doit prendre en compte les probabilités de bonne détection, de transmission correcte du contexte et l'existence de points durs. Les pannes de mode commun (réseau de bord, environnement physique), la propagation des pannes dans les structures, les doubles pannes... peuvent conduire à des performances très éloignées des performances théoriques.

3.3.2. - L'implantation locale des techniques de détection et de recouvrement des pannes permet à performances égales de diminuer le volume matériel total. Les ressources à mettre en oeuvre dépendent des sous-ensembles considérés.

3.3.2.1. - Interfaces d'entrée-sortie

Les tests de vraisemblance sur les valeurs et leur gradient, la prévision de l'évolution des paramètres peuvent être complétés par le calcul des paramètres manquants ou par la mise en place de redondances au niveau des capteurs et des conditionneurs.

3.3.2.2. - Les unités centrales à microprocesseurs

A moins de concevoir spécialement un microprocesseur autotestable, il est pratiquement impossible de définir une stratégie conduisant à un autotest à haute efficacité, on fera donc appel, si nécessaire, à la structure de la figure 17 qui bien que nécessitant 4 unités conduit à un gain de consommation par rapport à un système triplex, facilite la reconfiguration, réduit le nombre de points durs (horloge et comparateurs

autotestables).

Il est à noter que des unités autotestables peuvent être réalisées avec des circuits à très haute densité d'intégration.

3.3.2.3. - Les mémoires

Les moyens à mettre en oeuvre dépendent de la taille mémoire, de la durée des missions, de l'état de la technologie (organisation de la mémoire et modes de défaillance) ainsi que du temps accordé à la détection et au recouvrement des pannes. Les techniques appliquées pour de grandes capacités mémoire ou pour les durées de mission des satellites ne sont pas transposables directement pour des régulateurs numériques où la taille du programme est comprise entre 1 et 4 k mots, celle de la mémoire de travail étant de l'ordre de 64 mots.

La détection et le recouvrement des pannes des mémoires peuvent faire appel aux moyens suivants :

- *La checksum* appliquée au niveau d'un bloc de mémoire morte permet de détecter 100 % des erreurs simples et environ 95 % des erreurs doubles. Des variantes -somme arithmétique, calcul des résidus- améliorent cette efficacité. Pour la mémoire programme, la cheksum peut être appliquée en mode d'autotest ou en mode de reprise lorsqu'une panne est détectée par des chiens de garde naturels.

- *La parité* (plan bit) est applicable si l'on dispose de mots de 1 bit ou si on organise la mémoire en mots de 1 bit. On peut adjoindre une parité croisée ou un codage vertical à la mémoire programme et corriger l'effet d'une panne détectée si on accepte une dégradation du temps de lecture qui se révèle dans la plupart sans effet notable au niveau du temps d'exécution du programme (figure 18).

- *les techniques de codage* en particulier les codes de Hamming détecteurs et correcteurs d'erreur sont particulièrement efficaces pour des mémoires de grande capacité (figure 19).

- *Les techniques lourdes* de redondance massive ne sont pas à écarter compte tenu de l'augmentation permanente des densités d'implantation (64 kbits sur un chip) et de la réalisation des voteurs au niveau des unités centrales.

3.3.2.4. - Les liaisons

Les liaisons qui comprennent les fils de câblage et les émetteurs-récepteurs associés constituent des points durs en particulier dans les systèmes multiprocesseurs. La transmission en mode série parallèle qui assure un bon compromis entre la vitesse des transferts, la réduction du volume matériel, est fiabilisée par des techniques de redondance cu/et de codage, comme celles appliquées aux mémoires.

3.4. - AMELIORATION DES TAUX DE PANNE DES COMPOSANTS

Les pannes des composants électroniques restent inévitables malgré les progrès de la technologie. La prise en compte de leur existence lors de la conception permet d'en minimiser les effets sur le comportement du système mais ne résoud pas complètement les problèmes :

- de subsistance des points durs,
- de disponibilité des systèmes (on a vu pour ce faire, proposer des structures à onze calculateurs triplés),
- de maintenance (diagnostic et réparation imparfaits avec leur effet négatif sur la sécurité).

Le taux de panne des composants peut être réduit par divers moyens :

- choix des filières technologiques appropriées et connaissance fine de leur comportement,
- choix des techniques de déverminage tant pour les composants que pour les ensembles,
- qualification des fournisseurs,
- contrôles d'entrée renforcés.

Par ailleurs, la majorité des pannes étant induites par des contraintes extérieures, une bonne connaissance de l'environnement du régulateur électronique permet de mettre en place des moyens destinés à en réduire l'agressivité.

On peut espérer que l'ensemble des actions précitées permettront d'obtenir pour les régulateurs électroniques des taux de pannes analogues à ceux des systèmes hydromécaniques (KUH, 76).

4. - CONCLUSION

Les circuits à haut niveau d'intégration, en particulier les microprocesseurs, ouvrent de nouvelles perspectives dans l'élaboration des systèmes de régulation de moteur. L'utilisation d'outils rigoureux d'analyse et d'évaluation est nécessaire pour faire les nombreux choix techniques qui conduisent aux structures les mieux appropriées.

La diversité des architectures possibles permet d'envisager des solutions adaptees dans chaque cas aux objectifs fixés. Pour les applications simples, des regulateurs compacts et économiques sont réalisables. Pour les applications plus complexes, de hautes performances sont accessibles par l'adoption de microprocesseurs puissants ou d'architectures multiprocesseurs. Ces derniers constituent également la base de régulateurs sûrs de fonctionnement raisonnablement réalisables.

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(KUH 76) : J.F. KUHLBERG et D.M. NEWIRTH - Digital Electronic Propulsion Control System Problems and Payoffs - Journal of Aircraft Vol. 13, N° 4, Avril 76.

(LAP 75) : J.C. LAPRIE - Prévision de la sûreté de fonctionnement et architecture de structures numériques temps réel réparables - Thèse de Docteur d'Eta, 669-1975 - Université Paul Sabatier de Toulouse.

Paramètre	Nom	Capteur	Signal	Type
Position manette	α	Resolver	sin α, cos α	AC
Température entrée	Tt2	Sonde platine	R(Tt2)	Résistif
Pression statique	Ps4	Pont de jauge	V(Ps4)	DC
Régime moteur	N	Roue phonique	R/N, N	Fréquence
Température sortie	Tt7	Thermocouples	V(Tt7)	DC
Section tuyère	S10	Potentiomètre inductif	K S10	AC
Positions doseurs	C1, C2	Resolver	sin θ, cos θ	AC
Commandes, états		Switches		T/R

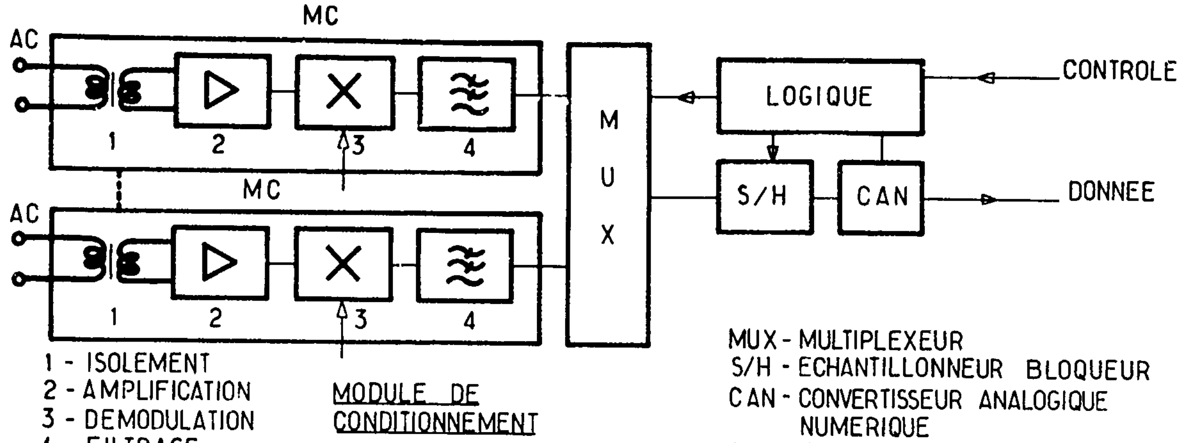
AC porteuse à 1000 c/s

DC bas niveau

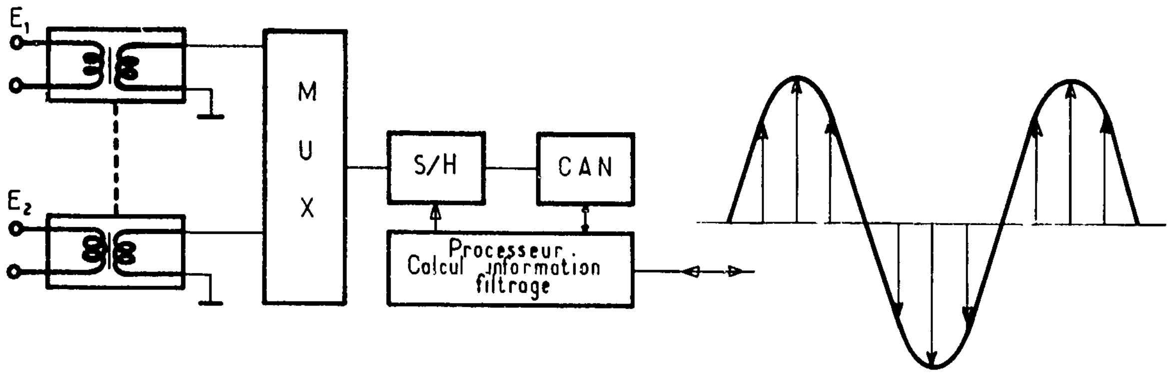
T/R tout ou rien 0-28 V

PRINCIPAUX PARAMETRES DE LA REGULATION

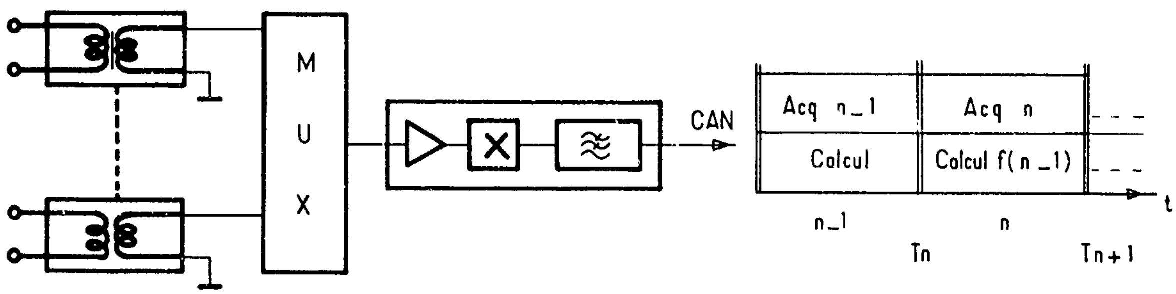
FIGURE : 1



ORGANISATION CLASSIQUE FIGURE 2.1

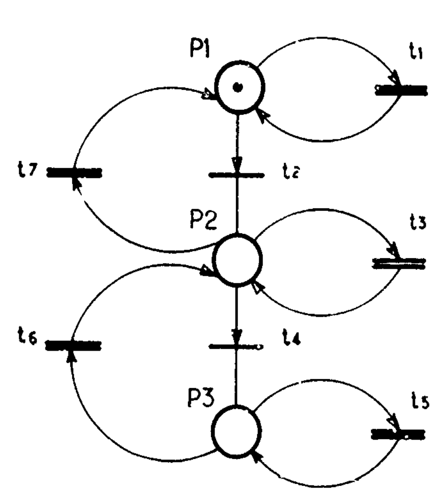


ECHANTILLONNAGE DIRECT
FIGURE: 2.2



MULTIPLEXAGE DU DEMODULATEUR
FIGURE 2-3

TRAITEMENTS POSSIBLES DE CAPTEURS DE POSITION
FIGURE 2



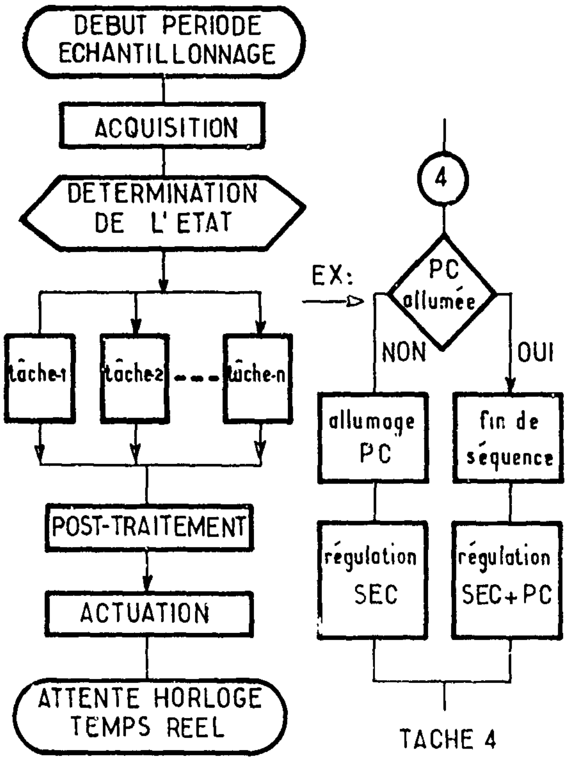
P1 - éteint

P2 - "sec"

P3 - sec et postcombustion (PC)

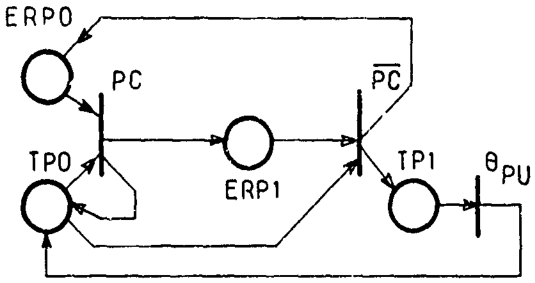
t_1 - attente surveillance
t_2 - allumage
t_3 - régulation sec
t_4 - allumage PC
t_5 - régulation + PC
t_6 - extinction PC
t_7 - extinction moteur

EVOLUTION DE L'ETAT DU MOTEUR
FIGURE: 3



ORGANIGRAMME GENERAL DE LA REGULATION

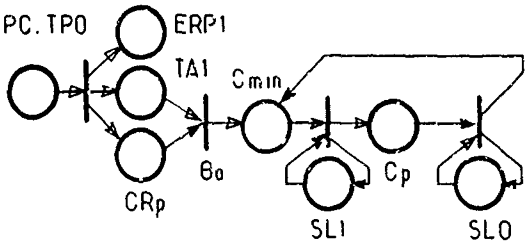
FIGURE 4



ERP 0 électrorobinet primaire non excité, 1 excité
TP 0 1 temporisation purge
θ — temporisation terminée
PC — top PC

COMMANDE DE L'ELECTROROBINET PRIMAIRE

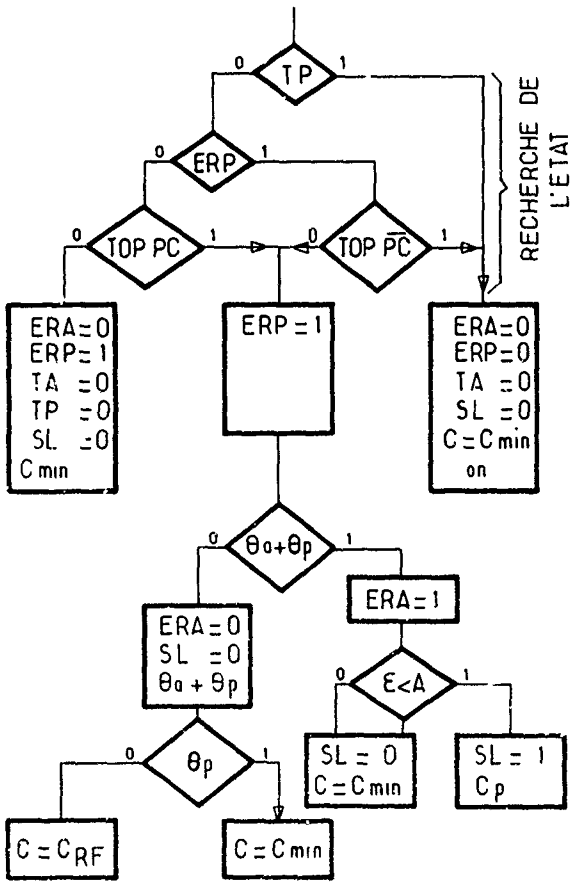
FIGURE 5-1



TA - temporisation allumage
CRP-débit de remplissage
Cmin-régulation de débit mini
SL - séquence libre f(N, SLO)
CP- débit pilote

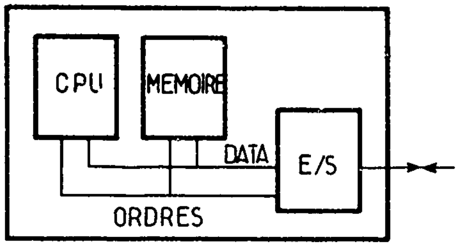
COMMANDE DES DEBITS

FIGURE 5-2

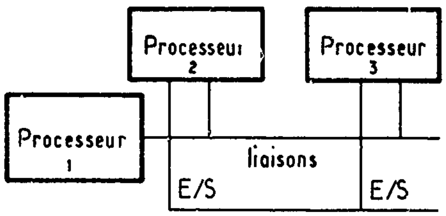


ORGANIGRAMME ALLUMAGE PC

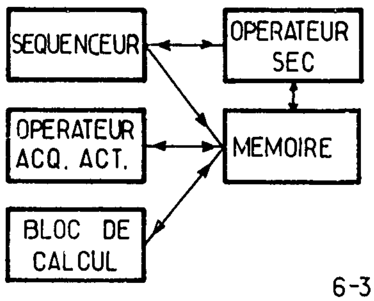
FIGURE 5-3



6-1 MINI CALCULATEUR



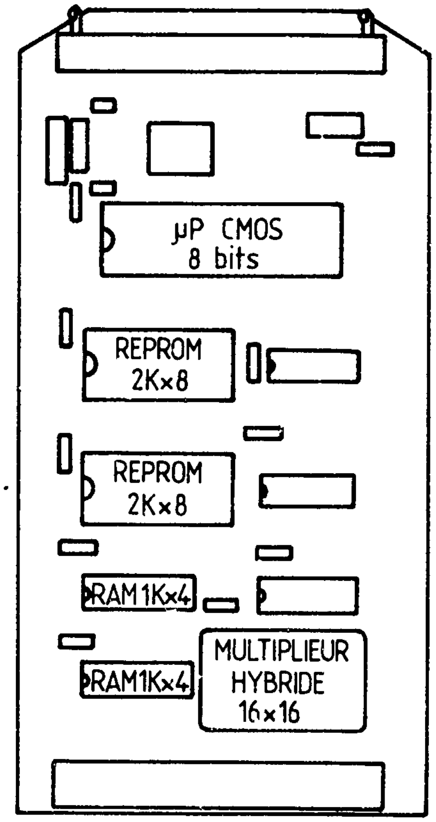
6-2. MULTIPROCESSEUR BANALISE



6-3. OPERATEURS

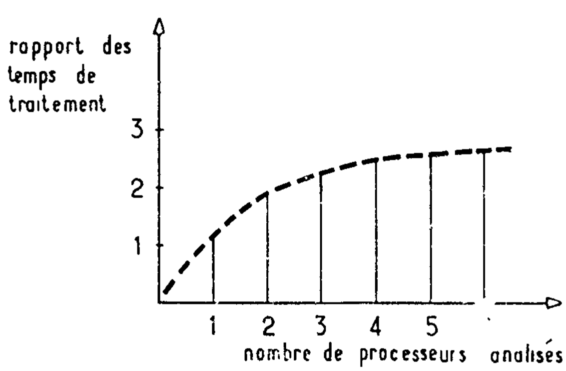
STRUCTURES GENERALES

FIGURE 6



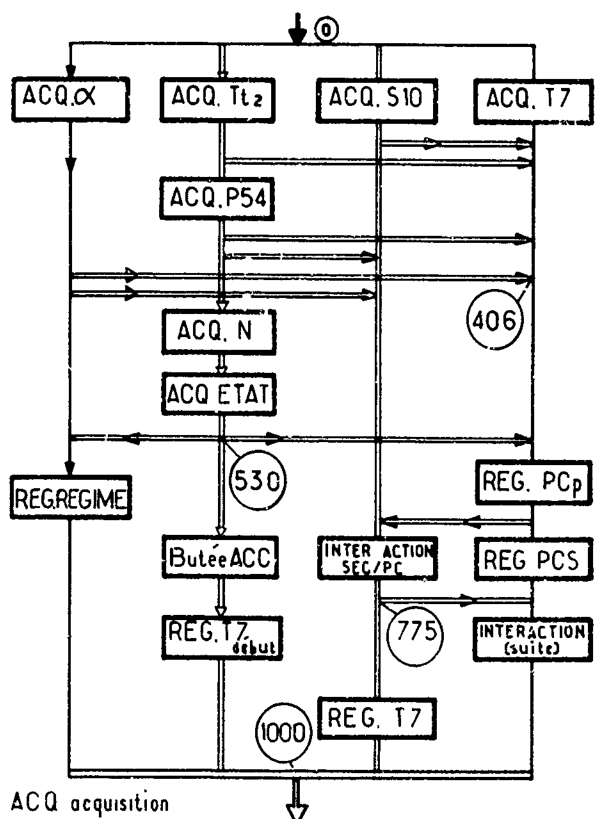
PROCESSEUR TYPE MINICALCULATEUR

FIGURE 7



CAPACITE DE TRAITEMENT

FIGURE : 8



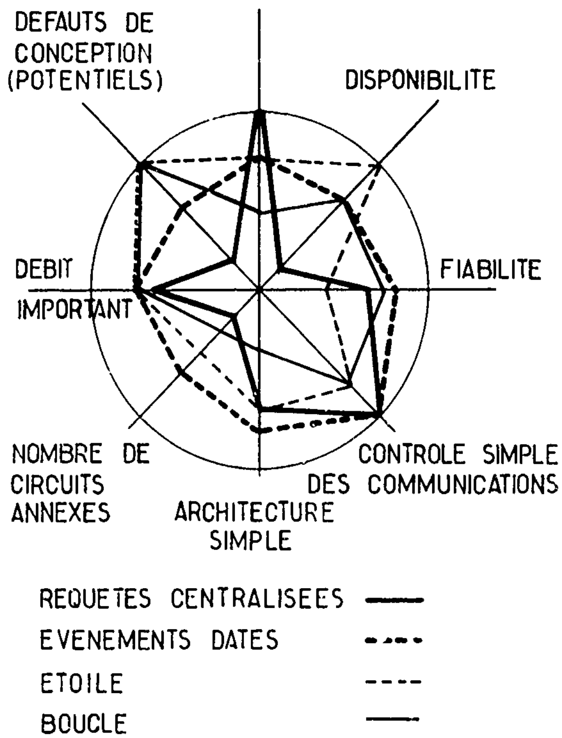
ACQ acquisition

REG. regulation

○ date des évènements (unité arbitraire)

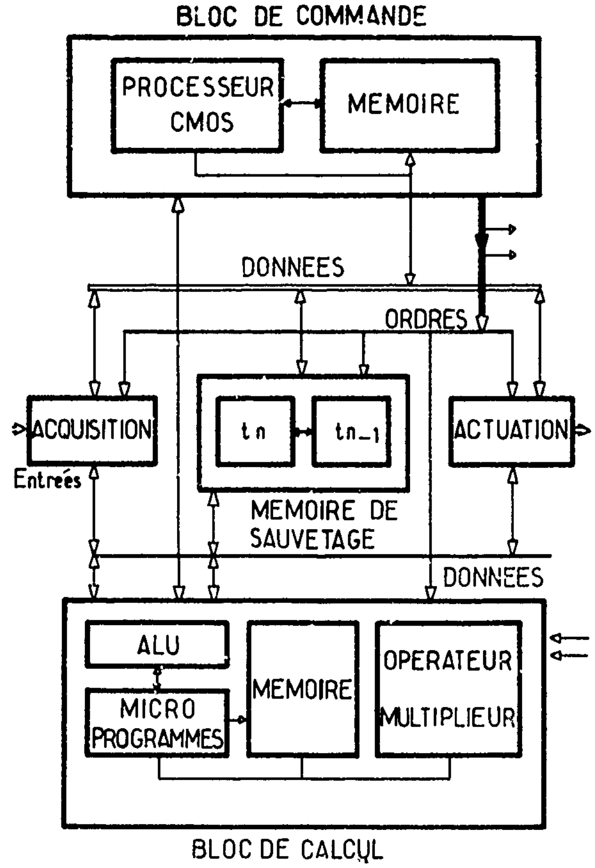
PROGRAMME DE REGULATION

FIG. 9



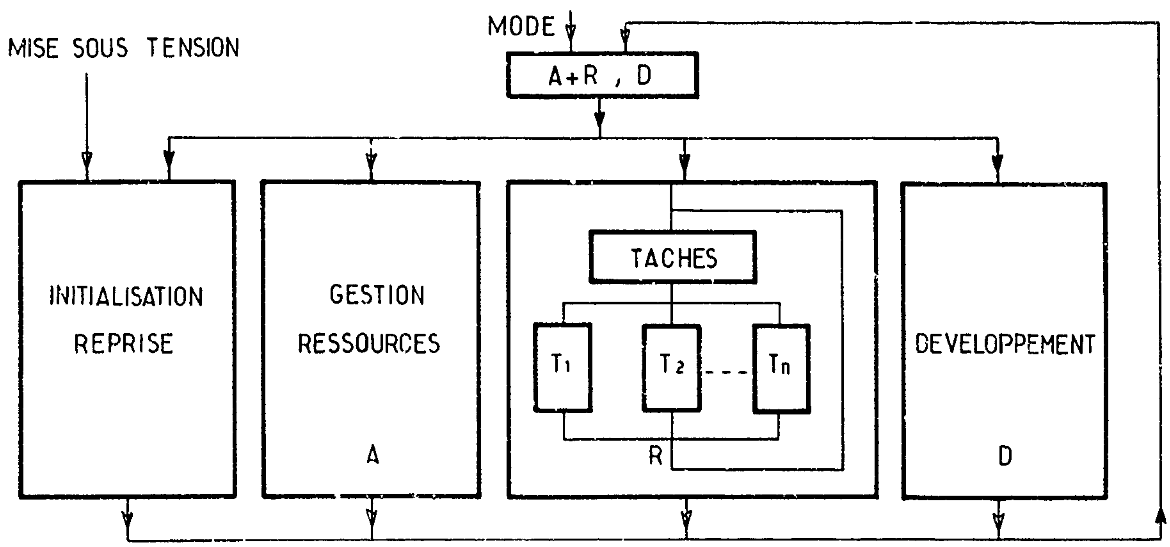
CRITERES D'EVALUATION D'UNE STRUCTURE MULTIPROCESSEUR

FIGURE: 10



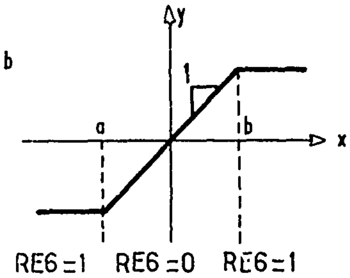
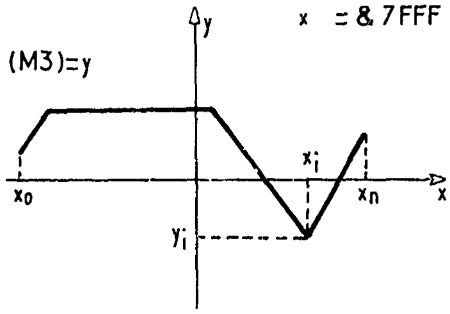
ASMARA . STRUCTURE FONCTIONNELLE

FIG :11



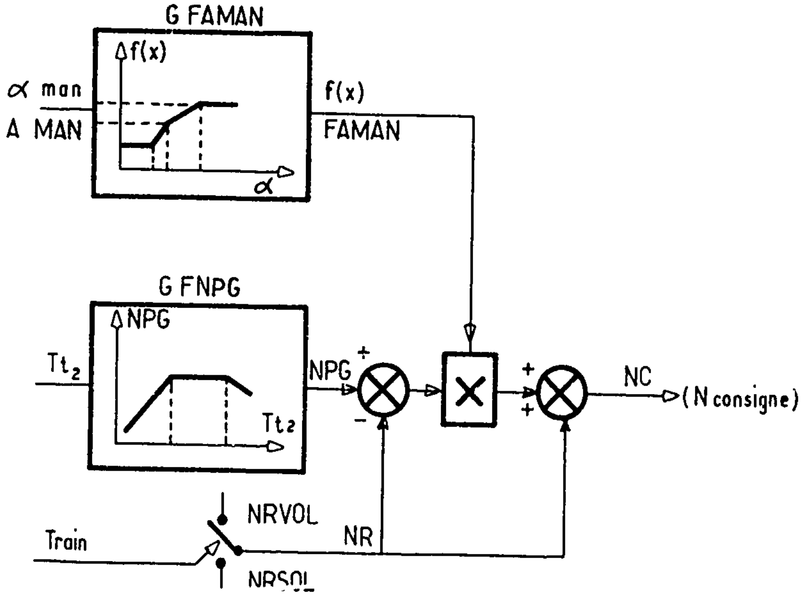
ORGANISATION MONITEUR

FIGURE: 12

	SYNTAXE	FONCTION	TEMPS D'EXECUTION (Appel compris)
Saturation	SAT M1 ;M2 ;M3	(M1) = x (M2) = a , b (M3) = y 	$x < a$ 9 μS $a \leqslant x < b$ 11,5 μS $x \geqslant b$ 10,5 uS
Générateur de fonction	GEF M1, M2, M3	(M1) = x n segments ⩽ 8 (M2) = x_0, y_0 · x_n, y_n x_0 = & 8000 x = & 7FFF (M3) = y  $\lvert x_i - x_{i-1} \rvert < 1$	60 μS + 4x (x = nbre de segments)
Interpolation	ITP M1 ; M2	(M1) = α , y , x $\alpha x + (1-\alpha) y \longrightarrow$ M2	40 μS
Dérivée	DER M1 , M2	(M1) = e_n , e_{n-1} (M2) = s_n $s_n = \frac{e_n - e_{n-1}}{2}$	9 μS
Intégrale	INT M1,M2,M3	(M1) = e_n (M2) = A, y_1, y_2 y_1 : saturation + (M3) = $s_n(1)$ y_2 : saturation − $s_n = A\,e_n + s_{n-1}$ si saturation RE6 = 1 sinon RE6 = 0	28/32 μS

EXEMPLE D'INSTRUCTIONS SPECIALISEES

FIGURE .13




```
           :
           GEF     AMAN , GFAMAN , FAMAN
           BRCO    TRAIN ; CTACH1
           TRA     NRVOL ; NR
           BRA     CTACH2
CTACH1     TRA     NRSOL ; NR
CTACH2     GEF     TT2 ; GFNPG ; NPG
           ITP     FAMAN ; NC
           :
GFAMAN     DATA    &8000
           DATA    &0000
           DATA    &8334
           DATA    &0000
           DATA    &14FD
           DATA    &44DD
           DATA    &647A
           DATA    &7FFF
           DATA    &7FFF
           DATA    &7FFF
GFNPG      DATA    &8000
           DATA    &9C29
           DATA    &BED3
           DATA    &3F5F
           DATA    &3D70
           DATA    &3F5F
```

Programme

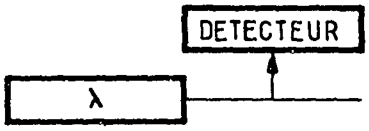
Description des générateurs de fonction

EXEMPLE DE PROGRAMME

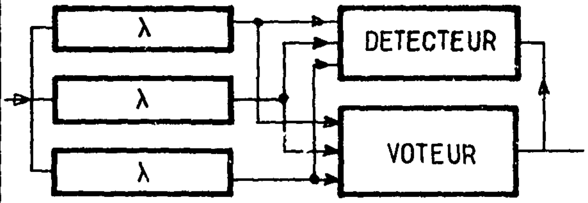
FIGURE : 14

SYSTEMES

SIMPLEX : S



TRIPLEX : T



P_D : efficacité de détection

k : % des points durs / structure

ETATS

1S - La structure fonctionne

2S - La structure est en panne détectée

3S - La structure est en panne non détectée

1T - Tous les sous-ensembles fonctionnent

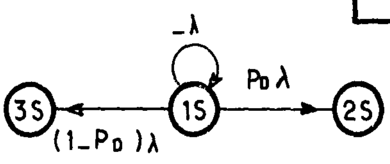
2T - 2 unités U et le point dur k fonctionnent 1 unité est en panne détectée

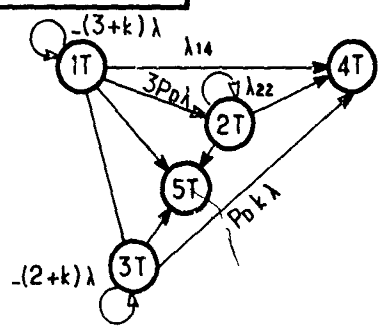
3T - 2U et K fonctionnent 1U est en panne non détectée

4T - Panne détectée de 2U ou du point dur

5T - Panne non détectée du point dur ou - Panne de 2U dont une au moins non détectée

GRAPHES DES TRANSITIONS





PROBABILITES Pi D'ETRE DANS L'ETAT i

$P_{1S} = e^{-\lambda t}$

$\dot{P}_2 = P_1\lambda_{12}$ $\qquad P_2 = P_D(1 - e^{-\lambda t})$

$\dot{P}_{2T} = P_{1T}\lambda_{12} - (\lambda_{24} + \lambda_{25})P_{2T}$

$\dot{P}_{2T} = P_{1T}\lambda_{12} + \lambda_{22} P_{2T}$

FIABILITE R(t) POUR $\lambda t = 5.10^{-4}$

$R = P_{1S}$

$\boxed{R_S = 1 - 5000.10^{-7}}$

$R = P_{1T} + P_{2T} + P_{3T}$

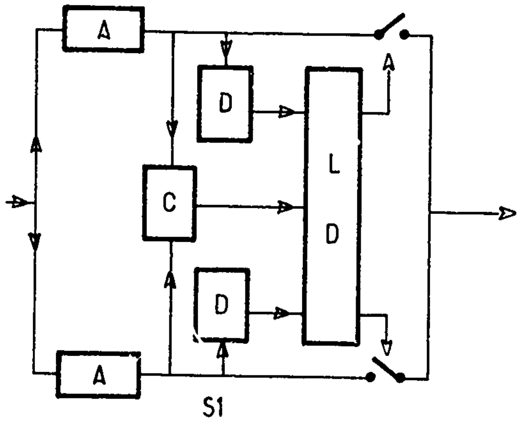
	% Points durs		
	0 %	10 %	20 %
R_T	$1-7{,}5\ 10^{-7}$	$1-507\ 10^{-7}$	$1-1007\ 10^{-7}$

SECURITE POUR $\lambda t = 5.10^{-4}$

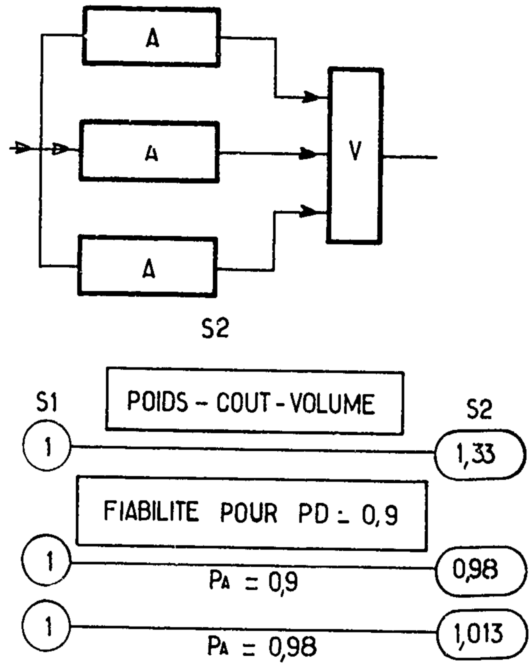
	Pour une efficacité de détection P_D =			
$S_S = 1$	1	$S_T = 1$		
		0 %	10 %	20 %
$S_S = 1 - 250.10^{-7}$	0,95	$1-0{,}73.10^{-7}$	$1-25{,}7.10^{-7}$	$1-50{,}7.10^{-7}$
		0 %	10 %	20 %
$S_S = 1 - 500.10^{-7}$	0,9	$1-1{,}4.10^{-7}$	$1-51.10^{-7}$	$1-101.10^{-7}$

" LES GAINS SPECTACULAIRES "

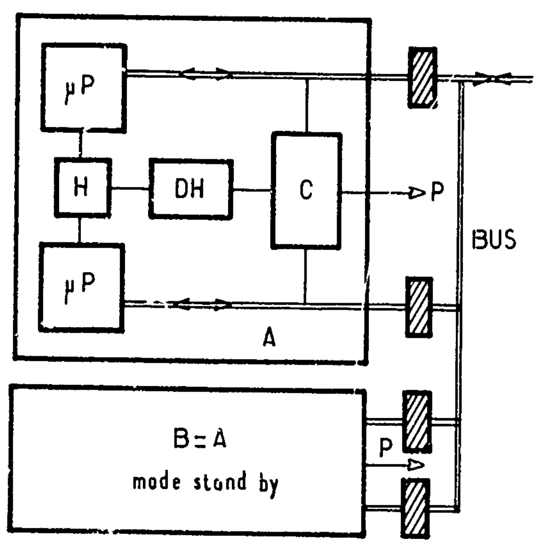
FIGURE 15



A - UNITE FONCTIONNELLE
D - DETECTEUR (code, parité ..)
C - COMPARATEUR AUTOTESTABLE
LD- LEVER DE DOUTE (autotest de D)
V - VALEUR



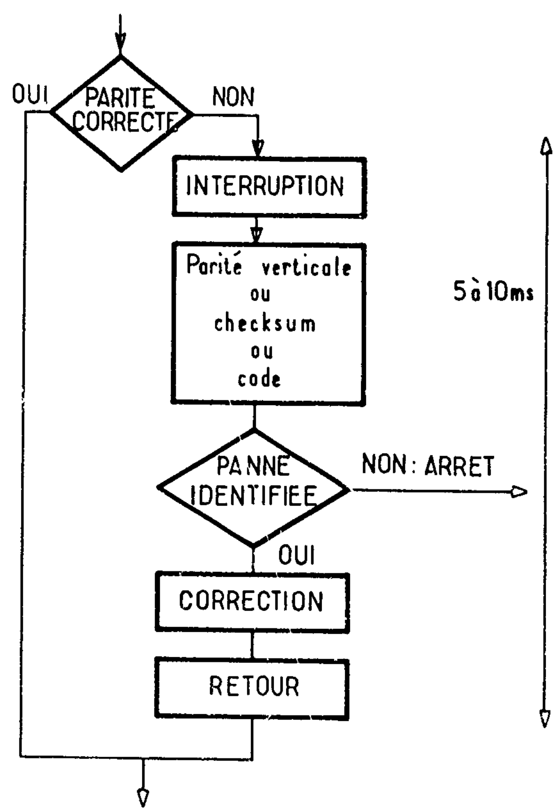
PERTE DE FIABILITE
FIGURE : 16



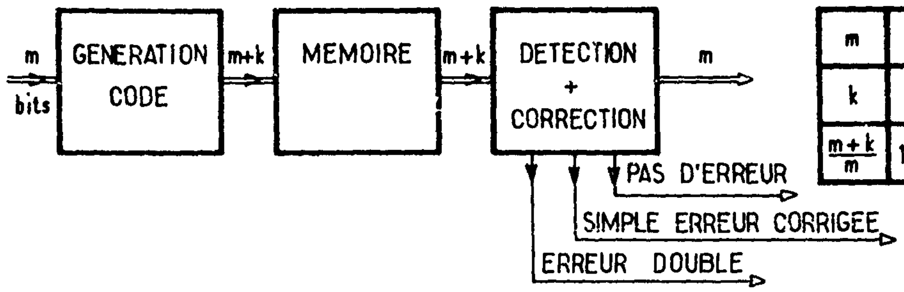
H+DH-horloge autotestable
C - comparateur auto-testable
▨ - isolation des pannes (résistances...)

UNITE CENTRALE

FIGURE : 17



RECOUVREMENT DES PANNES
(MEMOIRE PROGRAMME)
FIGURE : 18



m	16	24	32	48
k	6	6	7	7
$\frac{m+k}{m}$	1,37	1,25	1,22	1,1[illegible]

$(2^k \geqslant m+k+1)$

MEMOIRES: CORRECTION ERREUR SIMPLE DETECTION ERREUR DOUBLE

FIGURE: 19

DISCUSSION

J.Dunham, UK

What type of microprocessor do you use? How many microprocessors do you consider necessary (in a single control lane) to achieve satisfactory control of reheated engine?

Author's Reply

– We have been using a) IM 6100 12 bit CMOS
b) Intel 3000 2 bits-slice

– now after evaluation
RCA 1802 8 bits CMOS
2900 AMD a bits slice

– tomorrow – CMOS/SOS version of 6800
– CMOS/SOS version of 2900

– we refuse dynamic MOS microprocessor
I^2 L. too early – monosomie

Reheated engine
functional: 4 x 1802 or 1 micro – programmed 2900.
16 bits slice

I.S.D.Stitt, UK

Keyword-Reconfiguration: The paper says that in the event of a microprocessor's failure in a multiprocessor the computation is reconfigured so that the system will continue to give correct control outputs. Can the author say how this reconfiguration of the tasks performed by the microprocessors is achieved?

Author's Reply

The main processor (permitted by technique of massive redundancy) detects the fault and stops the outputs for 20 to (50?) ms, after which it seeks a new table of tasks in keeping with the reconfiguration.

Provided that the number of processors is sufficient, performance is maintained in full, otherwise operation continues with reduced performance. In the worst case, resort is made to the hydromechanical emergency control.

D.Mouranche, Fr

In your personal experience, have you been able to establish progress in the reliability of components parallel to progress in the performance and miniaturisation?

Author's Reply

Where progress concerns complexity and number of functions offered Yes.

In reliability or even only in availability for military purposes No
(Manufacturers develop cars and washing machines)

THE DESIGN CONCEPT AND EXPERIMENTAL RESULTS USING THE INTEL 8080/8085 MICROPROCESSOR

by

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SUMMARY

Having been involved for over twenty years in gas turbine control systems, the advent of the microprocessor gives an ideal opportunity to improve on both the system control aspects and the unit cost. The choice of microprocessor is fundamental to the capability expected but the following discussion concentrates on how the INTEL 8080/8085 series were chosen to meet the requirements of a simplex fuel control system.

Prototype flight equipment has been built using the 8080A and is flying with full authority in a twin engine helicopter. Isochronous load sharing on torque with simultaneous data logging output of transducer inputs and control functions is provided for monitoring purposes.

This detailed background is providing valuable insight to the true flexibility of a microprocessor controller and also illustrates any shortcomings that the later generation devices will need to overcome.

A fundamental CPU speed increase from 2 MHz to 3 MHz using the 8085 gives an immediate improvement and further margin for growth on current 8080 designs. Power supply simplification for single rail devices are also significant in reducing the complexity of construction and cost.

The final main impact of any microprocessor R. & D. activity is the ability to re-use previously developed software. Where the unit cost is continually falling so does this element become more significant. Because of upward compatible software for the 8080/8085 series, a library of control software has been built up which can now enable new control schemes to be implemented to high confidence levels within weeks instead of months.

CHOICE OF MICROPROCESSOR

For gas turbine engine fuel control system tasks, the main criteria for the choice of a microprocessor are as follows:-

(1) Sufficient speed and software repertoire to be able to undertake the control tasks in the time available.

(2) Proven semiconductor technology offering the required basic reliability to the components and in-volume production.

(3) Well supported microprocessor development equipment with appropriate software aids to speed application developments, and reduce the amount of first-time software.

(4) A powerful supporting chip set for the basic microprocessor, thus reducing the overall system component count and, if smart interface chips are available, generally increasing its overall speed capability.

(5) For Military applications, the chip set, including microprocessor, must be available to the required temperature range of -55°C to +125°C and meet BS9000 or MIL-STD-883, preferably with JAN or BS9400 approval.

(6) Multi-sourced microprocessor and supporting chip set ensuring flexibility and continuity of supply.

Review and experience of several devices employing different semiconductor technologies and with data word lengths ranging from 8 to 16 bits concludes in the selection of the INTEL 8080/8085 series for simplex fuel control applications. The devices considered are all rated for operation over the full temperature range, and include:-

MANUFACTURER	PART NUMBER	DATA WORD	TECHNOLOGY
Intel	M8085A	8 bits	NMOS
Intersil	IM6100A	12 bits	CMOS
Texas Instruments	SPB9900A	16 bits	I^2L

Previous experience has shown that it is desirable to perform fuel flow calculations with a resolution of at least 10 bits (.1%) and that the programme cycle time should be short enough to allow the calculation to be updated approximately every 16 milliseconds. The advantages and disadvantages of the various processors may be summarised as follows:-

(a) INTEL M8085A

The 8 bit data word requires the use of double precision arithmetic in some calculations, but this is facilitated by a number of instructions which operate on register pairs. 8 bit operation also fits in well with the use of standard memories.

The instruction set lacks multiply/divide instructions, necessitating the use of external hardware or software routines. Depending on the application, a balance is struck between using a hardware multiplier (also now available as a single rail device), or the extra memory and processing time that a software alone approach implies. We have developed certain software techniques which allow critical fuel flow calculations to be updated in the required time without additional hardware. These have already been successfully demonstrated using the 8080A. With the 8085A speed increase of 50%, the same routines can be used with even greater safety margins. The single 5V power supply of the 8085 also overcomes the other disadvantages of the 8080A's more complex supply requirements.

The semiconductor manufacturer is fully committed to the development of Military temperature range components, the 8080A being the first microprocessor to be JAN qualified, with an M38510 slash sheet. Similar action is anticipated for the 8085A which is second-sourced. Above all, the microprocessors are fully supported by a family of compatible interface components, and it is these that enable very low component count controllers to be configured. For future growth INTEL is developing a family of software compatible devices including:-

(1) 8086 - a 16 bit microprocessor with advanced instruction set

(2) 8088 - a 16 bit microprocessor with 8 bit data bus, ideally suitable for upgrading from 8085

(3) 8048 - an 8 bit single chip microcomputer

The whole microprocessor family is extremely well supported with hardware and software development aids.

(b) INTERSIL IM6100A

At first sight the 12 bit data word appears ideally suited for the resolution requirements. However, since most standard memories are partitioned into 8 bit words, it proves to be wasteful of memory. The lower power CMOS technology is an advantage in some applications, particularly battery powered, and the microprocessor is second-sourced.

The processor uses the Digital Equipment Corporation PDP-8E instruction set. This makes available a very extensive repertiore of proven software techniques but the instruction set is now outdated and limited compared with more recent developments.

The other major disadvantages are its slow operation, and the absence of multiply/divide instructions, necessitating the use of external multiply hardware.

Although the microprocessor has now been available for several years, there has been little evidence of the development of compatible interface components, and more advanced processors.

(c) TEXAS INSTRUMENTS SPB9900A

Experience of similar control requirements has been gained on this device and the INTEL 8080. It is a 16 bit microprocessor with a powerful instruction set, including multiply and divide, making it possible to meet the resolution and programme cycle time requirements with a very straightforward software approach.

The 16 bit processor requires fewer words of memory than the 8 bit design, with double precision arithmetic, but the double word length results in the use of somewhat more memory overall. The 16 bit data and address busses result in the need for a large (approximately 76 mm x 25 mm) 64-pin package. The device is one of a fairly extensive family of compatible parts, but most of the other components are only available in limited temperature range TMS (NMOS) version, e.g.

(1) 9980 - a 16 bit processor with 8 bit data bus

(2) 9940 - a single chip computer version of the 9900

Although the processor has been available for approximately two years, there is still no second source for the full temperature range version. This, together with its more limited application, results in the cost remaining relatively high.

(d) SUMMARY

With the above experience, and considering the complexity of typical gas turbine controls, especially in the helicopter field, the 8085A microprocessor is selected as the most suitable. It offers the lowest cost approach, both in the microprocessor itself and its supporting hardware. Based on trials already carried out using the 8080, the speed increase from the 8085 will leave sufficient capacity for future growth and incorporation of added features such as data logging and certain health monitoring functions.

SOFTWARE STRUCTURE

With the upwards compatible nature of the software evolved for the INTEL 8080/8085 series microprocessors it is useful to consider how the control system is built up. The software system is put together in modular blocks of programme, each block performing clearly defined functions, e.g. Nf governing, system initialisation, etc., generally having one entry and one exit point. This leads to increased software reliability. Each software block is developed using facilities offered by INTEL's ISIS-II system, resident in MDS-80/ICE-80/ICE-85. Tye ISIS-II assembler or PLM compiler generates a relocatable object code file, from an assembler source module, which can be linked subsequently with other modules needed to complete the software system.

Thus, during development a module would be linked into a test environment for debugging purposes. The tested module would then be linked into its final system, with full confidence that the tested performance will be maintained.

The software package during development resides on floppy disk media as a number of module files. Each module will have an assembler source code file, with its relevant object file described above, as well as a list file, generated at assembly/compiler time. Also resident on disk is a file containing all the modules linked together, which is transferred to memory giving a runnable software system. Speed of programme run time operation within the confines of maintaining programme modularity has been used as the highest criterion during software design and development. Thus, a higher run time speed will always be achievable at the expense of software reliability, and diminished returns during the development period. As with all fast software systems, speed gives rise to the use of increased memory space. This is not seen as a particular problem in the light of the tendency of increasing memory space with decreasing cost.

For example a straightforward shift and add/multiply technique, using in-line coding, rather than a looping system, will provide speed at the expense of the use of extra memory.

As an illustration of the control software library built up by our Company using the INTEL family of microprocessors whilst running on the test bed various gas turbines, the latest flight demonstrator system utilises nearly 50% of existing software modules. With the benefit of these trials it is expected that future controls would require less than 30% of new software which can be seen as a tremendous benefit in choosing such a family of microprocessors.

As fuel control systems are fast acting, the software timing plays a critical part in the execution of the various control packages. To aid the structuring of the software, and its appropriate timing, a major/minor cycle map is produced that separates the high priority and low priority tasks.

The major cycle is that time in which all control tasks must be carried out, which in most aero engine control systems, usually lies between .1 to .5 seconds. The minor cycle is that time within which some control tasks must be serviced to achieve control stability. For the typical aero engine, this usually requires a rate of servicing between 16 and 20 milliseconds.

Within this framework the major/minor cycle map is then constructed to optimise the process of throughput while meeting the control stability requirements. Our experience to date has indicated this results in a major cycle being composed of between 8 to 32 minor cycles, depending on the complexity. The sampling and subsequent processing of each input signal is performed at a rate consistent with the frequency content and response time of that signal and its associated control loop. In a typical helicopter control the throttle angle, torque, and speed achieved signals are processed at full rate. The remaining inputs are processed at slower rates, but not less tha every major cycle.

This multiple sample rate technique has the dual advantage of minimising truncation errors caused by sampling at too high a rate, and of avoiding the necessity of performing all functions within the sample period required by the highest frequency loop, and gives flexibility in avoiding input aliasing problems.

The general software structure as outlined enables the majority of failure checking software also to be completed within each minor cycle. Based on a nominal 16 milli-second minor cycle, the main software response from a fault to a freeze on the output actuator would occur within this time. It is important to structure the output actuator and its relation to the number of steps in any direction so that the failure response is achievable within a relatively small fuel flow and hence engine power change.

The memory capacity for a current 8085 design providing full simplex control of a helicopter is typically 6K by 8 of ROM and 500 words of RAM.

PROCESSING OF INPUT SIGNALS

The very efficient peripheral components of the 8085 system enable a very efficient circuit structure resulting in the complete interface being configured using very few discrete components. This has a direct bearing on reliability and cost.

Speed Signals

A single LSI chip can process three frequency signals simultaneously once they are suitably filtered and squared from the raw signal source. The software organises the rate of access to the registers containing the speed information on the LSI chip, rather than using an interrupt. It is only necessary to provide sufficient counts within the sample time to meet the resolution requirements. To meet a .1% resolution, at least 1,000, and generally more counts, are required, and using the sample period of 16 milli-seconds frequency multiplication is usually necessary.

This is achieved using phase locked loops and low pass filtering is effected around the loop thus minimising noise and frequency modulation effects.

With the slower 8080 the added benefit of having frequency as a direct value instead of, as is usually the case for interrupt measuring systems, a value proportional to the period of the incoming frequency, the requirement for a divide operation was avoided. With the faster 8085, avoidance of this task may not be so necessary, and a more optimum hardware structure will be configured.

Analogue Signals

The various analogue signals are multiplexed in a conventional 12 bit analogue to digital converter, operating directly under the microprocessor control. This results in optimum sampling of those signals with respect to the control system requirements.

For low signal inputs, such as thermocouples, software manipulation of both signal and reference voltages is carried out, so that automatic gain and offset changes with temperature and time are automatically carried out. This is typical of the features that a microprocessor can offer over the conventional analogue approach which would require very expensive components to achieve the same order of accuracy.

OUTPUT INTERFACE

Almost all of the fuel control systems operate in conjunction with a multi-phase stepper motor. For aircraft systems, this is more desirable as the failure mode is intrinsically fail-freeze. The fundamental design concept of utilizing the intelligence of the microprocessor to its full is seen in this function. The requisite bit pattern that ensures clockwise or anti-clockwise rotation is totally software generated, prior to 'writing' to the peripheral output circuit.

Furthermore, a separate gating function is interposed between the peripheral and each power switch such that pulse width modulation of the stepper motor phase drive takes place as a function of the aircraft supply voltage. The actual timing is generated by a counter/timer peripheral component under direct software control. During severe transients, where high slew rate demands exist, maximum power is delivered to the stepper motor for the appropriate period, again, dictated by software analysis of the actual valve position compared to the demanded step input. In this way, dissipation in the stepper motor is minimised without prejudicing torque requirements for control purposes.

Serial Output Interface

The availability of communication chips that are directly supported on the bus structure of the microprocessor adds a bonus to the basic controller. The ability to talk to, interrogate, and to receive data from a controller in parallel with its primary control tasks, provides the system designer with test features (on the ground and in flight) and a source of engine and airframe parametric information suitable for other processing needs.

Whilst great care must be taken to establish the integrity of the primary controller when such a serial interface is operational, the power of the microprocessor enables quite significant data transmissions to occur even in the background time relative to the main programme. Our experience to date has shown that as many as 30 8 bit parameters could be output every ½-second at a processing time of only 150 microseconds per 16 millisecond minor cycle for the 8080A and proportionally less for the 8085. This data can be any parameter that the controller has access to, as well as any internally generated function. This feature is very useful during the flight trials as a close monitor on control system performance and fault diagnosis.

The I/O port discussed is based on the industrial RS232C protocol but for future avionic systems the ARINC or MIL-STD-1553 standards are usually desirable or mandatory.

Already, the INTEL 8080/8085 bus structure can now support an off-the-shelf system comprising a specially microprogrammed controller mounted on a single ATR compatible printed circuit board. This unit could service such a bus, yet not place the high demands on the engine control processor. In fact, the circuit is designed to appear as another addressable peripheral, and compatibility with 1553, 1553DAIS or 1553B is achievable with PROM changes only.

IMPROVED CONTROL SCHEMES

The ability of a digital system to generate complex functions relatively easily compared to the complex circuitry for the equivalent analogue controller, enables the system designer to more closely match the controller to the engine. Our particular experience is illustrated by the ability to provide cooler starts (of the order of 50°C) for a given engine by shaping the start and temperature limiting functions.

This is an area where the engine manufacturer is particularly conscious from the point of view of engine life. Also from the operational point of view, the pilot is usually looking for consistent starting times, in the case of VSTOL aircraft, faster and more consistent accelerations under varying engine and ambient conditions. Successful control schemes have been implemented whereby acceleration on fixed or variable Ndot (rate of change of gas generator speed) have eliminated the variation of engine performance from ambient air temperature and engine conditions in achieving idle and maximum speeds. The flexibility of the digital controller approach means that various alternative starting schemes can be tried during development, thus optimising performance for any production design. So long as the required input parameters are available in the basic control, these alternative schemes would require only software re-arrangement.

Integration of fully automatic start schemes, whereby ignition and starter relays come under direct control of the fuel control system, provide for more total integration of the engine controller. Good experience has been gained to date on industrial gas turbine start/stop sequencing systems, and the benefits of providing the complex inter-locks usually required have been realised. The ability to provide for a variety of control schemes for the primary loop or loops implies on the basic design concept that sufficient memory and processing power is available. Experience on five widely varying gas turbine applications, namely

(1) An industrial standby generating set

(2) A high performance vectored thrust engine

(3) A marine gas turbine

(4) Two very different gas turbines for medium helicopter applications

has resulted in the optimum memory requirement illustrated previously.

INTEGRITY AND RELIABILITY

As our experience lies particularly in the helicopter controls field, where the simplex control is advocated, with an alternative manual reversionary control, the concept of integrity bears some importance. It is normal with conventional analogue control systems to provide some form of safety circuit to prevent throttle runaway up or down, in the event of a component failure. The microprocessor digital controller provides this facility because most of the possible failure modes produce complete freeze of the control system. There are, however, still some modes of failure particular in the read only memories, which may produce runaway up or down, but whose failure can be detected by internal checks, which form a particular part of the digital control software programme.

The analogue to digital converter and multiplexer are checked by having one channel with a fixed reference voltage whose value the computer checks for correctness every sample period.

The analogue circuits which input to the control system are checked at circuit level for validity and frequency inputs are checked for their correct 'window' of operation, relative to other engine parameters. The stepper motor and resolver are checked continuously by virtue of the overall software technique utilised, which compares the movement of the resolver for a given series of step demands, so that either item can be checked for gross failures and any parametric deteriorisation of the resolver itself. A given number of steps must always result in a certain angular movement through the gearbox and resolver.

It is generally arranged that during a start up sequence, the stepper motor is exercised over a small number of steps, and the corresponding resolver movement checked. During this brief cycle the above checks will automatically be carried out and the pilot would have an early warning of any fuel metering element malfunction prior to engaging the starter.

Because the multi-phase pulse train to the stepper motor is software organised a very high integrity system results. In all the microprocessor controllers developed to date, this has involved the processor in going to memory for a look-up table, returning and outputting the correct multi-phase pulse train to drive the motor and then returning to its original task. Errors in the multi-phase pulse train invariably cause the motor to freeze. In this manner, therefore, a whole host of processor features must work correctly for the actuator to be driven at all, and the failure modes of the processor being able to correctly do this task, and incorrectly do other tasks are extremely remote.

Our current design philosophy for recording any malfunction is to enter the fault occurrence and its cause as determined by the safety checking software into non-volatile memory (EAROM - Electrically Alterable Read Only Memory). Devices are now on the market that have full Military temperature range operation with read/write cycle life limitations far in excess of any practical requirement.

The ability to have access to this form of memory via a serial I/O will provide valuable fault diagnosis information on those faults that may be intermittent and not reproducible on the ground.

Conservative reliability predictions for a typical airframe mounted microprocessor controller are in the region of 10,000 to 20,000 hours. This is already compatible with the well proven analogue approach, and is expected to mature as experience is gained in service use.

CONCLUSIONS

All the experimental results to date during the various engine trials and development tests point to the wider acceptance of microprocessor controllers for stringent control requirements. The initial concern whether the microprocessor could meet the performance goals, especially the 8 bit family such as the INTEL 8080/8085, has now been dispelled. Furthermore, the sensitivity of digital circuitry to the harsh RFI and EMC environments has not been seen as a problem. Current designs have satisfied MIL-STD-461A and MIL-STD-704A tests whilst the packaging and environmental aspects are relatively straightforward.

The 'on-engine' microprocessor controller that replaces its hydromechanical equivalent is now available with competative price, weight and reliability factors. Performance, growth and flexibility have now been proven to be significantly greater than the analogue counterpart which leaves the engine and airframe manufacturer wide scope for system improvements.

DISCUSSION

D.T.Hawes, Ca

Why don't you use interrupt driven Foreground-Background scheme thus utilising the 30–50% capacity apparently wasted in the scheme described.

Author's Reply

The spare capacity is designed in to ensure a software margin of safety. However, there are tasks carried out in this time, e.g., displaying parameters on a serial communications line, that can be interrupted, and also which do not require to be complete within each minor cycle.

W.Merrill, US

Your presentation indicated most of your μP controls are mounted but that you are beginning to look at off-engine mounted controllers. What is your motivation for doing so? What location philosophy do you intend to adopt in the long term? Do you anticipate resistance to off-engine mounted μP controls from airframe manufacturers who might use your engine control systems.

Author's Reply

The motivation for an off-engine controller is primarily the basic cost comparison of the controller itself. Milder temperature and vibration requirements allow simpler solutions within the controller and generally the fewer mechanical constraints allow for more optimum and cost effective packaging.

Either location can be made available depending on engine/airframe requirements. The on-engine philosophy is superior from an interface point of view.

Yes, from the integrity aspects. No, from the overall cost point of view. However, very often for small to medium helicopters, the distance between an engine-mounted environment and airframe is only a few feet.

J.M.Collin, Fr

(1) Why have you not used Ferranti?

(2) Is μP standardised in Great Britain?

(3) Have you encountered problems with dynamic operation at elevated temperatures?

(4) Do you believe complicated peripherals will be available for military purposes?

Author's Reply

(1) For commercial applications cost is the main objection and our company has chosen to use the INTEL range for all avionic applications.

(2) No.

(3) No – because of the structured format in that all tasks must be completed within defined time limits, temperature effects are not applicable.

(4) Yes. As has been demonstrated on most peripheral components, full military temperature range and quality processing is being applied to the most popular elements – those that make up the heart of the central processing system.

R.Smyth, Ge

Key word: Engine Health Monitoring. What type of engine health monitoring is used? Is it limit exceedance control or does it monitor pressures, temperatures and fuel flow as a function of $N/\sqrt{T_1}$ on the well known non-dimensional basis?

Author's Reply

Health monitoring in conjunction with the control tasks is at the moment limited to transducer validation and cross-correlation to other engine parameters.

As the power of the processor extends so will be incorporated true health monitoring and even trend analysis based on the non-dimensional parameters and gas path analysis. Separately – these tasks have been accomplished using the INTEL series of processors in the field of Industrial Gas Turbines and the software and mathematical approaches will be combined into the avionics field.

I.S.D.Stitt, UK

Key word. Fault Tolerance. The paper claims that the software was fault tolerant but the example given was that the software was re-initiated and ignored transiently detected faults. The question requested the author's definition of fault tolerant software and for examples.

Note. Fault tolerant software is generally considered to refer to software so designed to continue to give the correct system output whilst faults exist in packs of the software and/or associated hardware.

Author's Reply

Fault tolerant software was illustrated as a Software System that could enable the control system to recontinue after a software "glitch" or absurd set of dynamic conditions that were not evaluated during the test stage.

The fact that these conditions went transiently outside the design limits for the software to handle in its allotted time, should not necessarily "freeze" the system on one ocurrence. If they continue to reappear then they must be regarded as a more fundamental fault and different criteria applied.

K.Smyth, Ge

Key word. Software Development. What type of computer language is used in the software development phase? Any higher level language?

Author's Reply

Assembly language is used for the control tasks in all cases. For some software modules associated for example with Health Monitoring and data transmission, PLM high level language was used.

DESIGN, EVALUATION AND TEST OF AN ELECTRONIC, MULTIVARIABLE CONTROL FOR THE F100 TURBOFAN ENGINE

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Summary

Modern aircraft turbine engines include a variety of control actuators which affect the performance and response of the propulsion plant. The incorporation of digital processing permits integrated control action to meet strict steady-state and transient performance requirements. The need exists for a control design procedure that can account for multiple loop interaction and can make efficient use of them to enhance performance without decreasing engine stability margins. The F100 Multivariable Control Synthesis Program was a cooperative effort with the Air Force Aero Propulsion Laboratory and the NASA Lewis Research Center aimed at investigating the use of extended linear quadratic synthesis techniques to accomplish the design, evaluation and testing of a practical multivariable control for the F100 engine.

A digital, multivariable control design procedure for the F100 turbofan engine is described. The controller is based on locally linear synthesis techniques using linear, quadratic regulator design methods. The control structure uses an explicit model reference form with proportional and integral feedback near a nominal trajectory. Modeling issues, design procedures for the control law and the estimation of poorly measured variables are presented.

The multivariable control law was implemented on a general purpose minicomputer at NASA Lewis Research Center. The logic was thoroughly validated against explicit design and operating performance criteria on a real time hybrid simulation of the engine throughout the full flight envelope. Alternate control modes, sensor failure sensitivities and other design features were investigated using the hybrid simulation.

The resulting system was then used to operate an actual F100 engine in an altitude test facility at NASA Lewis Research Center. In all, steady-state and transient performance were investigated at five (5) subsonic and four (4) supersonic test points. The results of these experiments and correlation to the important design issues are presented.

Nomenclature

A	= trim switching matrix
A	= quadratic state weighting matrix
A_j	= nozzle area
B	= quadratic control weighting matrix
BOM	= bill of material (production) control
C	= feedback gain matrix
C_x	= regulator gain matrix (m x n)
C_y	= integral gain matrix (m x r)
D	= linearized measurement matrix
f	= nonlinear engine model
F	= linearized engine dynamics matrix
H	= linearized measurement matrix
H	= Hamiltonian matrix
h	= nonlinear measurement function
h	= a row of the H matrix
n	= number of states
N	= rotor speed
m	= number of controls
P_3	= burner pressure
$P_{4.5}$	= interturbine volume pressure
P_6	= augmentor entrance pressure
p	= number of outputs
q	= number of parameters
r	= number of possible trim variables
S	= steady-state Ricatti matrix
T	= state transformation matrix
$T_{2.5H}$	= fan exit inner temperature
$T_{2.5C}$	= fan exit outer temperature
T_3	= compressor discharge temperature
T_{4HI}	= high turbine inlet temperature, high response
T_{4LO}	= high turbine inlet temperature, response
T_4	= high turbine inlet temperature, local
$T_{4.5HI}$	= fan turbine inlet temperature, high response
$T_{4.5LO}$	= fan turbine inlet temperature, low response
T_5	= fan turbine exit temperature
T_{6C}	= augmentor entrance temperature
T_{7M}	= augmentor exit temperature
u	= m x 1 control vector
x	= n x 1 state vector
y	= p x 1 output vector
u_s	= m x 1 control reference point vector
x_s	= n x 1 state reference point vector
y_s	= p x 1 output reference point vector
z	= model coordinate
r	= vector of parameters
w	= perturbation quantity
$\Delta p/p$	= fan exit Mach number parameter
Λ	= block diagonal matrix
Ξ	= model controllability matrix
λ_j	= eigenvalue

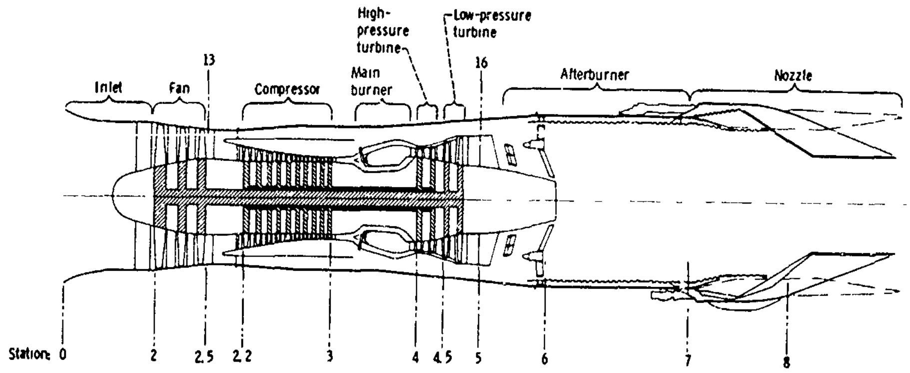

Figure 1 - Schematic representation of F100-PW-100 augmented turbofan engine.

Introduction

Over the past several years, aircraft operational requirements have dictated the development of propulsion systems having increased performance over a wider operating envelope. To satisfy these performance requirements, variable geometry components have become an integral part of advanced aircraft engines. Future variable cycle engines may incorporate variable fan, compressor, turbine and exhaust nozzle geometry to improve overall performance.(1) As a result, the engine control system will have to be capable of controlling engine fuel flows and the variable geometry in an "optimum" manner. This will necessitate the measurement of more engine variables. However, the multitude of variables to be manipulated and measurements to be utilized make it difficult to design controls for these advanced engines.

Classical control synthesis techniques, which involve the analysis and design of single-input, single-output control loops, have worked quite well for the older, simpler engines. Unfortunately, such techniques prove to be cumbersome and time-consuming when they are applied to the more complex multivariable engines.

One approach to solving the engine control problem is the use of multivariable (optimal) control theory. The Linear Quadratic Regulator (LQR) is one aspect of the theory that has been successfully developed and applied to a wide variety of linear multivariable control problems.(2) LQR designs result in feedback-type controllers which make use of inherent loop interactions to improve performance. The LQR control modes can also reduce the sensitivity to parameter variations and sensor inaccuracies.

The F100 Multivariable Control Synthesis (MVCS) Program[3,4,5] was a jointly sponsored Air Force Aero Propulsion Laboratory-NASA Lewis Research Center program designed to investigate the use of Linear Quadratic Regulator (LQR) theory to the design of a practical control for an advanced state-of-the-art turbofan engine. There have been some initial research and development efforts made at applying LQR theory to the design of controls for the nonlinear, gas turbine engine process.(6-10) These efforts, however, have been limited to engine control over a narrow operating range (usually sea level, static, standard-day conditions). The MVCS program differs from previous studies in that it addresses the following issues: (1) the ability to accomplish large power excursions without exceeding engine or actuator limits, (2) the extension of the controller authority to the entire engine operating envelope, (3) the consideration of sensor and actuator nonlinearities in the design process, and (4) the validation of the control performance in real time.

The F100 (see Figure 1) engine was selected for the MVCS program due to the availability of detailed digital and hybrid computer simulations of that engine and the availability of an actual F100 engine for testing at NASA Lewis Research Center. The F100 engine represents the current state-of-the-art in aircraft gas turbine technology. Although not as complex as some of the advanced cycles being proposed, the F100 does provide a suitable test for the LQR technique. In addition to the main burner and afterburner fuel flows, the F100 has variable fan inlet guide vanes, variable compressor stator vanes and a variable convergent-divergent exhaust nozzle. Airflow bleed can be extracted at the compressor exit.

Certain restrictions were placed on the control design. The design approach would use linear engine models as a basis for the control synthesis. Deterministic LQR theory was to be applied exclusively, i.e., as a first approximation, the random uncertainty associated with the engine behavior was assumed to be negligible. Only existing sensed variables were to be used as control inputs. The controller authority was to include engine operation from idle to max dry power. Start-up and afterburner regimes were excluded; however, during the hybrid simulation and engine tests, afterburner lights were done to assess the controller's regulation capability in the presence of disturbances.

Prior to the actual control design, detailed criteria were established that specified the desired engine performance.(3) The control criteria can be summarized as follows. Foremost, the control must protect the engine against surge and from exceeding speed, temperature and pressure limits. Airframe-engine-inlet compatibility requirements specify minimum burner pressure limits and maximum and minimum airflow limits at certain flight conditions. The control must insure engine thrust and fuel consumption are within tolerance for specified engine degradations and for installation effects. The engine must also accelerate and decelerate smoothly, safely, quickly and repeatably with small overshoots allowable. It must do this for both large and small requested power level movements and during flight maneuvers.

Theoretical Synthesis Method

The fundamental aspects of locally linear control synthesis are reviewed as applied to the synthesis of the control and the fundamental requirements of the control structure. The engine may be modeled conceptually as a nonlinear time-invariant dynamical system utilizing fundamental aerodynamic principles as follows:

$$\dot{x} = f(x,u,\theta) \tag{1}$$

$$y = h(x,u,\theta) \tag{2}$$

where n states, x, m controls, u,p outputs, y, and q parametric variables θ, as well as the detailed nonlinear dynamics f(.,.,.) and measurements h(.,.,.), are modeled by the designer to achieve his purpose most expediently. For engine development, detailed digital simulations, including thorough component maps and experimentally correlated gas path equations, are utilized as in the F100 transient simulation deck. These programs are too complex for control synthesis, but are useful in evaluating a candidate design.

Locally linear models can be generated from nonlinear simulations[3] or experimentally from engine data via system identification, e.g., Ref. 11. These models are valid in the neighborhood of an equilibrum point (x_0,x_0,θ_0) and describe perturbation motion $\delta x,\delta u$, away from equilibrium. These models are represented as follows:

$$\delta\dot{x} = F\delta x + G\delta u \tag{3}$$

$$\delta y = H\delta x + D\delta u \tag{4}$$

where, in principle,

$$F = \left.\frac{\partial f(x,u_0,\theta_0)}{\partial x}\right|_{x=x_0} \tag{5}$$

δx and δu will be rewritten as x, u in the remainder of this paper.

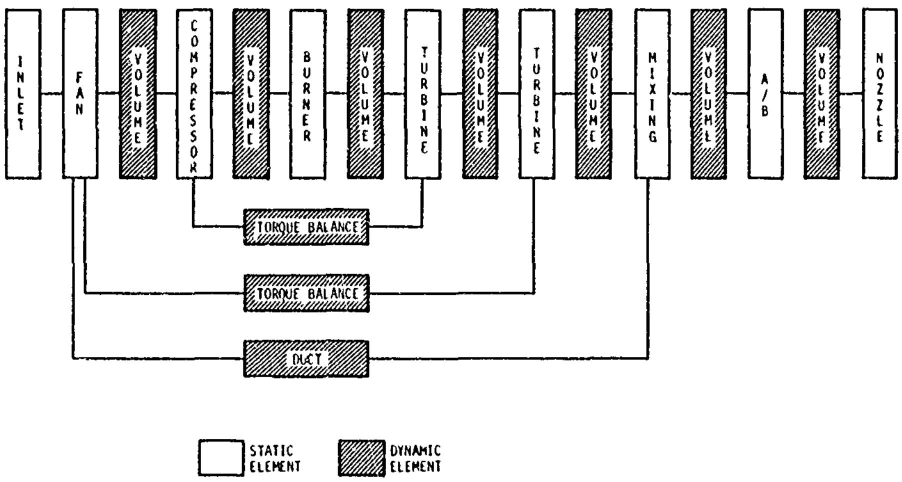

Figure 2 - Schematic Flow Diagram of F100 Nonlinear Digital Simulation.

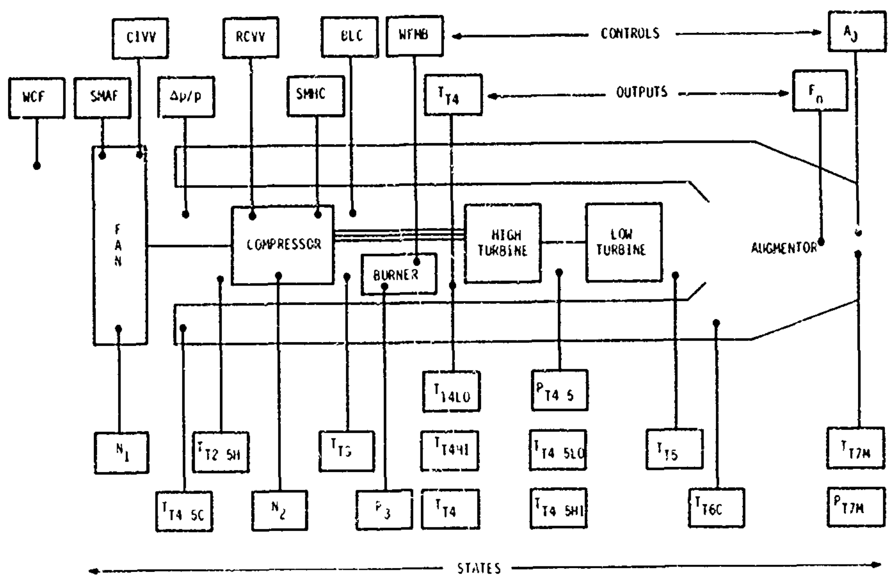

Figure 3 - States, Outputs and Controls Modeled in F100 Linear Equations Generated from Nonlinear Digital Simulation Program.

Figure 2 shows a schematic representation of the F100 digital transient simulation. Each dynamical element represents two or more states, and the entire linear model contains 16 state elements (Fig. 3). The linear model can be reduced in order to include only practically measurable elements and only important dynamics relative to the control objective.

$$\begin{bmatrix} x_1 \\ \hline x_2 \end{bmatrix} = \left[\begin{array}{c|c} T_{11} & T_{12} \\ \hline T_{21} & T_{22} \end{array}\right] \begin{bmatrix} z_1 \\ \hline z_2 \end{bmatrix} \tag{6}$$

$$\frac{d}{dt} \begin{bmatrix} z_1 \\ \hline z_2 \end{bmatrix} = \left[\begin{array}{c|c} \Lambda_1 & 0 \\ \hline 0 & \Lambda_2 \end{array}\right] \begin{bmatrix} z_1 \\ \hline z_2 \end{bmatrix} + \begin{bmatrix} \Xi_1 \\ \hline \Xi_2 \end{bmatrix} u \tag{7}$$

where x_1 and z_1 are the qth-order partition of states and modes and x_2 and z_2 are the (n - q)th-order partition.

Various guidelines for making the appropriate partition will be discussed below, in which case the following equilibration relation can be attained approximately within the time frame of interest:

$$\dot{z}_2 \simeq 0 \tag{8}$$

If relation (8) is valid, the following relations hold:

$$\dot{x}_1 = F_r x_1 + G_r u \tag{9}$$

$$\begin{bmatrix} x_2 \\ \hline y \end{bmatrix} = \begin{bmatrix} H^* \\ \hline H_r \end{bmatrix} x_1 + \begin{bmatrix} D^* \\ \hline D_r \end{bmatrix} u \tag{10}$$

The formula for the reduced matrices follow from elementary matrix algebra.(12)

Thus, by assuming that (n - q) modes are equilibrated, the nth order system (3) is reduced to the qth-order system (9) with q states and p + n -q outputs. It should be noted also that the q retained states x_1 are chosen by the designer (13) and possess the same physical identification in Eqs. 3 and 9 as long as Eq. 8 is approximately valid.

The partitioning of the system is dependent upon the control designer's estimate of the frequency range of the control function. For example, this F100 controller was designed primarily to modulate thrust in transient and steady-state operation. The response frequency range extends from 0 to about 10 rad/s, which is the bandwidth of the primary (fuel flow) actuator. The frequency range would be significantly different if, for example, the controller were designed to modulate compressor surge margin with a high-bandwidth, variable-area turbine actuator. The implication is that all eigenvalues significantly outside the bandwidth of interest are in equilibrium during the motion and may be partitioned with the (n - q) eliminated roots.

A special situation occurs when a state is nearly parallel to a single modal direction. If the outputs are not affected significantly by the particular element, then the state and associated dynamics can be removed from the design model without affecting behavior important to the control synthesis. Figure 4 shows the normalized eigenvectors associated with two eigenvalues for the F100 engine lying in the bandwidth of control. These modes are associated with temperature lag states at the turbine inlets. Examination of the thrust output equation shows that these states have a relatively small contribution. Thus, for control design purposes, the two states and the associated modes can be eliminated.

We have shown a number of techniques for choosing (n - q) modes that can be eliminated, along with a group of states. The choice of the retained q states is somewhat arbitrary, depending on convenient measurables as well as the dependence of important output quantities. The modal decomposition can be used to assure that the chosen q states strongly span the controlled subspace (T_{11} invertible and well conditioned). With this partition and associated reduction, the resulting system will represent a controllable design model.

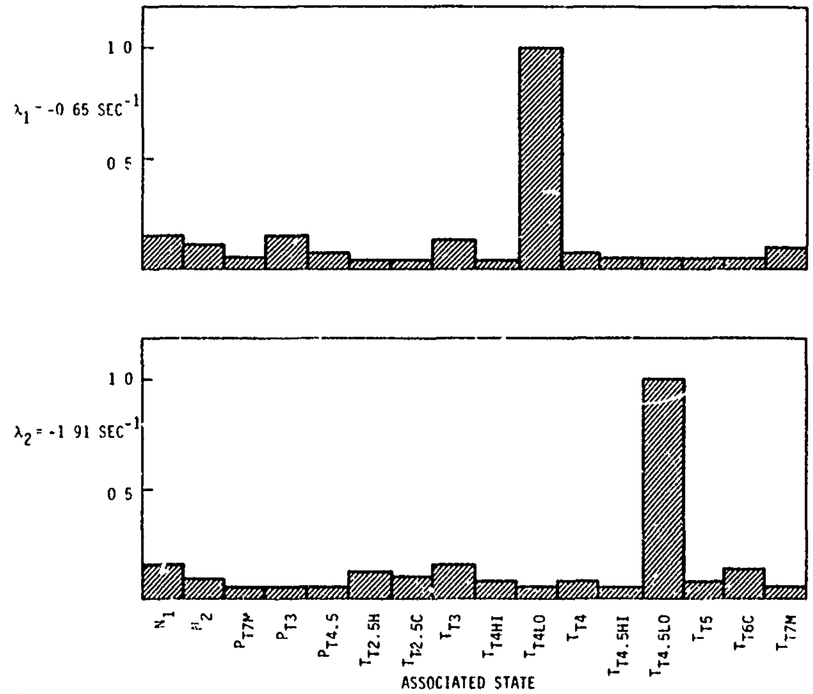

Figure 4 - Normalized Eigenvector Components for Two Roots Lying in the Bandwidth of Control at Sea Level Static, Intermediate Power Condition for the F100 Turbofan Engine.

For the F100, the behavior of the design model vis-a-vis the sixteenth-order linear system and nonlinear simulation is shown in Figure 5. The reduction was performed on the linear system equations in each region of the operating envelope to provide a set of models used in the optimal regulator synthesis. The total procedure to arrive most efficiently at multivariable designs requires the utilization of a blend of techniques incorporating frequency and time domain analysis and modern and classical control concepts.

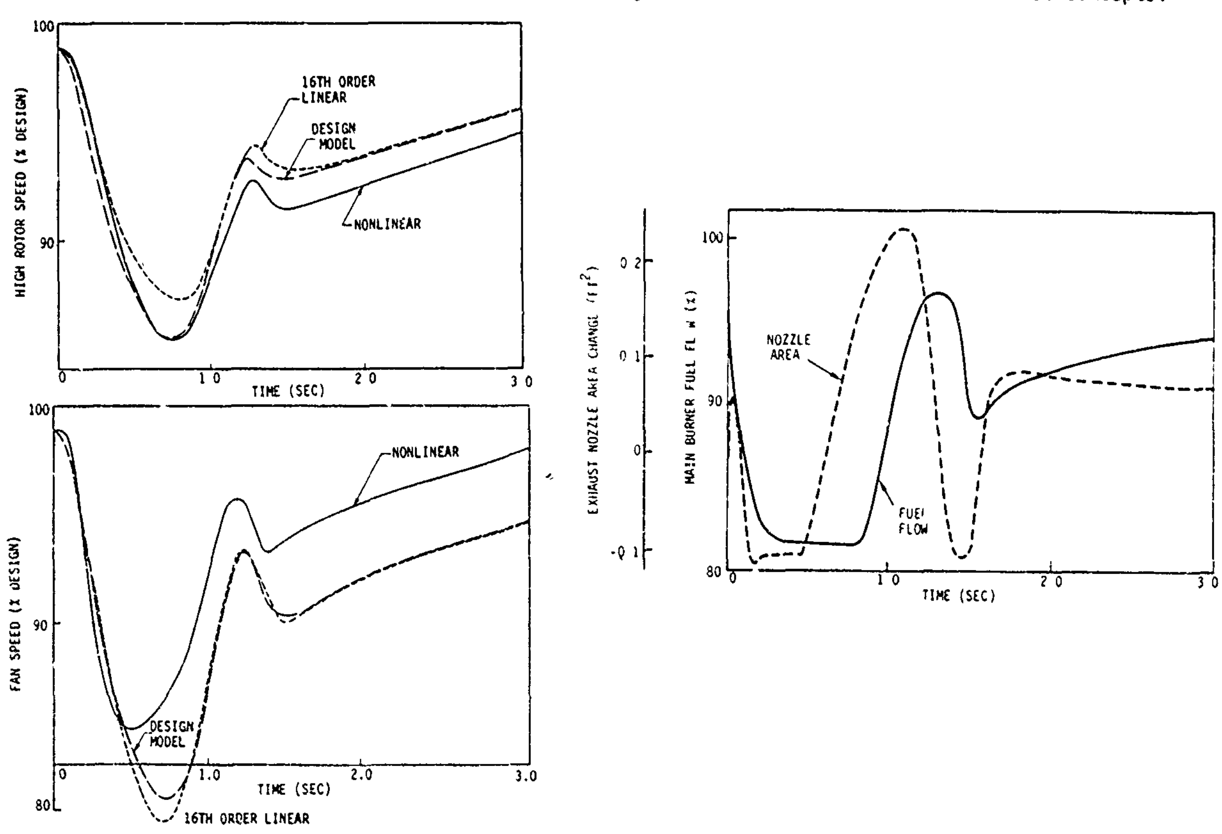

Figure 5 - Comparison of Small Perturbation Response of the F100 Turbofan Engine at Sea Level Static, Take-off Power Simulated by the Full Nonlinear Digital Deck, the 16th-Order Linearized Model and the Reduced Order Design Linear Model.

Given the linear design model (Eq. 9), and the state/control performance index,

$$J = \frac{1}{2} \int_0^\infty (x^T Ax + u^T Bu)dt \tag{11}$$

or the output performance index,

$$J = \frac{1}{2} \int_0^\infty (y^T A^* y)dt \tag{12}$$

the deterministic, steady-state optimal controller to minimize J for arbitrary initial conditions about a fixed set point is given by the following state variable regulator control law:

$$u = u_0 + C(x - x_0) \tag{13}$$

$$C = -B^{-1}G^TS \tag{14}$$

where u , x are a consistent equilibrium reference point for the nonlinear plant, namely,

$$0 = f(x_0,u_0) \tag{15}$$

where $f[x(t),u(t)]$ describes the nonlinear engine behavior exactly. The matrix S is given by the positive definite solution of the algebraic Ricatti equation (for Eq. 11)

$$0 = SF + F^TS + A - SGB^{-1} G^TS \tag{16}$$

and by a comparable form for Eq. 12. The solution is calculated numerically by integration of the matrix Riccati differential equation to steady-state or, more efficiently, by the eigenvector decomposition method.(14) The optimality of such regulators is given in terms of a fixed set point. However, with reasonable choices of weighing parameters, system response is not degraded for varying set-point inputs.

The state or output weightings can be constructed initially from physical reasoning. Alternately, if it is desired to alter the dynamic response in terms of time domain specifications (e.g., rise time or damping), state weightings on the variables most nearly associated with the mode to be controlled are chosen. State variables and output quantities often are related physically. Control of the state is then equivalent to control of the output. In this case, the need for explicit output weighting is removed. For example, engine thrust, an output and augmentor pressure, a state, have nearly the same coefficient representation. Thus, weighting P_{t6} results in direct control of thrust response. Such considerations can give the designer a foundation for the initial quadratic weighting matrix selection.

If a number of control requirements are represented in the performance index simultaneously, it is probable that the initial design will be unacceptable in some way. Often, the unacceptable nature of the behavior can be linked directly to a particular closed-loop root and modal response vector. For example, thrust overshoot can be linked to a P_{t6} $-N_1$ complex pair in the closed-loop root cancellation, as determined by an examination of the eigensystem. It is clear that the weights on either N_1 or $\cdot_{t6}$ or both must be adjusted so that the damping is increased. Sensitivities of the closed-loop locations to changes in weighting matrix elements can be calculated from decomposition of the Euler-Lagrange system used to solve the algebra Riccati equation.(15) For the decomposition,

$$HT = T\Lambda \tag{17}$$

with Λ diagonal and H the dynamics of the Euler-Lagrange system; it can be shown (15) that

$$\frac{\partial\Lambda}{\partial\theta_1} = T^{-1} \frac{\partial H}{\partial\theta_1} T \tag{18}$$

where,

$$\frac{\partial\Lambda}{\partial\theta_1} = \text{diag } \{\frac{\partial\lambda}{\partial\theta_i}j\} \tag{19}$$

is the sensitivity of the eigenvalue location to a change in the weighting. The matrix $\partial H/\partial\theta$ normally consists of 1's and 0's, and the similarity transformation is available from the optimal controller solution. Utilizing Eq. 18, the correct weight changes to alter the closed-loop pole locations is evaluated easily. Successive use of model weighting sensitivity and time domain simulation will result in the quick convergence to a design with acceptable regulator performance.

Functional Description of the Controller

Figure 6 shows a schematic representation of the digital controller. The control structure is applicable to many physical, nonlinear systems with state, control and output constraints. Each functional component of the system produces an element of the control law. The multivariable control law is expressed by Eq. 20.

$$u = u_s + C_x(x - x_s) + \int C_y A(y - y_s)dt \tag{20}$$

The feedback law itself represents an optimal regulator structure with integral trims for steady-state accuracy and a model following implementation to prevent saturation during transients. Each element of the control law will be described relative to the F100 implementation, and the synthesis procedure for each block will be reviewed briefly.

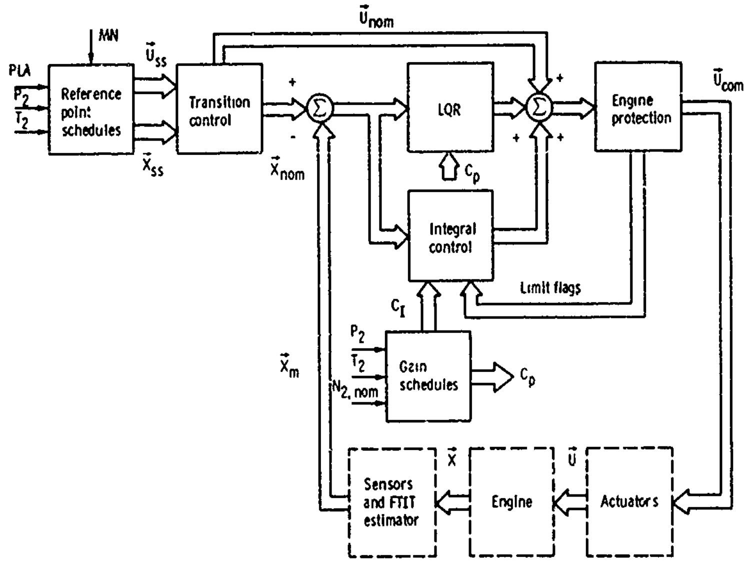

Figure 6 - F100 Multivariable Control System.

Reference Value Generator

The control law is written for state and control perturbations about an equilibrium condition. The equilibrium conditions must be derived approximately by the controller given the requested power level, altitude, Mach number, engine face pressure and temperature. Because of manufacturing tolerances and engine aging, an exact expression for these quantities is not possible. Inaccuracies in the scheduled reference values normally would cause steady-state "hang-offs" unless compensated with an integral trim action. Small inaccuracies do not degrade transient performance, and indeed, the feedforward structure allows lower regulator feedback gains and the associated model parameter insensitivity of the control.

The reference schedules are produced by calculating the thermodynamic equilibrium associated with a given control vector. The manufacturer-specified steady-state condition requires zero bleed flow and scheduled compressor geometry. Two degrees of freedom are left to attain desired thrust (power level) at a particular flight point. The reference point generator attempts to set a fan matchpoint to achieve equilibrium. The current control mode is to specify the fan matchpoint using fan rotor speed and fan exit Mach number ($\Delta p/p$).

A constrained minimization can be performed to determine the required fuel flow and and jet area to achieve requested thrust while optimizing a free variable, e.g., fuel consumption or surge margin, and respecting all engine structural limits. For comparison purposes in the F100 controller, schedules were generated to match the production control operating point at each power level and flight point.

A representative group of subsonic and supersonic flight points was chosen, and the engine equilibrium points were calculated. Nondimensionalized quantities were utilized to fit approximate reference points with minimum complexity. The regulator is tolerant of the schedule errors and produces smooth transient responses without an overly complex implementation.

Transition Model

When a large transition in power is requested by the pilot, the perturbation character assumed in the regulator design is lost. A large change in the reference state vector will cause large commanded inputs, tending to saturate actuators and produce significantly nonlinear behavior. The regulator can be used to track a compatible trajectory taking the system for one state to another. Exact calculation of such trajectories is complex,(16) and their practical implementation has not been investigated. A first-order approximation to an achievable state trajectory can be calculated directly from the linearized model, (Eqs. 3 and 4). In this case, it is assumed that

$$\dot{X} = R_X = \text{constant} \tag{21}$$

and, allowing for various controllability constraints, a consistent set of equilibrium state and control rates R_X, R_y can be calculated if a particular set of output rates is specified. The nonlinear trajectory $(x_s(t),\ u_s(t))$ then is approximated as follows:

$$\hat{x}_s(t) = x_s(t_0) + R_x t \tag{22}$$

$$\hat{u}_s(t) = u_s(t_0) + R_u t \tag{23}$$

where the transition is terminated when the new reference point is reached. The rates are derived from parametric fits of values calculated at each flight/power point. Figure 7 is a schematic diagram of the transition control logic.

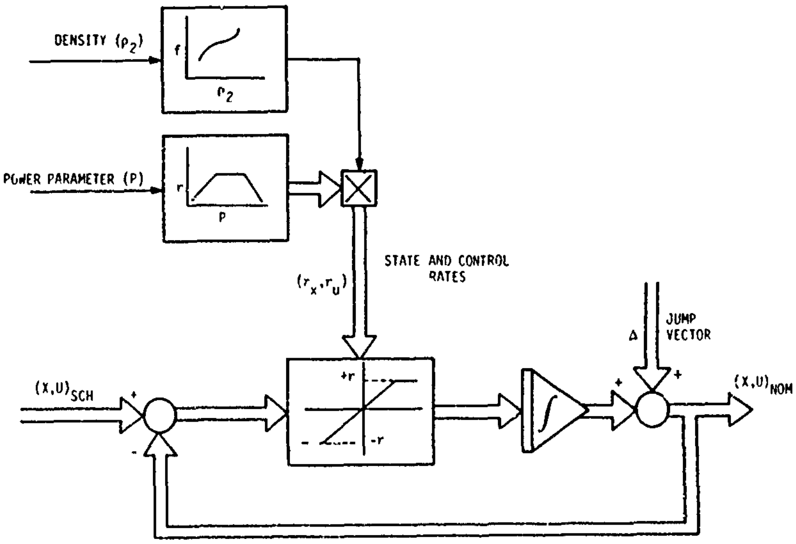

Figure 7 - Transition Trajectory Generation Algorithm is Formed from a Rate Limited Servomechanism Structure With Variable Rate Saturation Forming the Gross Trajectory and the Proportional Response Providing Continuity with the Steady-State Reference.

Notice that the term u_s from the trajectory generator is a feedforward control command in the control law of Equation 20. This feedforward feature produces rapid and smooth accelerations and decelerations without the need for high gain integrators. This is a highly desirable feature as integrators have a destabilizing effect on any system.

In the F100 implementation, rates were calculated for low, middle and high power. In the latter two cases, desired thrust and turbine inlet temperature rates characteristic of the engine were chosen. At low power, thrust and either burner pressure or surge margin rates were specified, depending on the flight condition, in order to specify adequate acceleration surge margin or eliminate burner pressure undershoot. Figure 8 shows the response of the nonlinear digital simulation to a large-power-level modulation. Engine state and trajectory time histories are shown, along with error terms in the regulator portion of the control law. The transition model prevents large error terms from saturating actuators during gross transients while still providing stiff regulation near steady-state conditions. The implementation of this type of transition algorithm requires very little control logic and storage. The performance is excellent and the processing overhead is minimal.

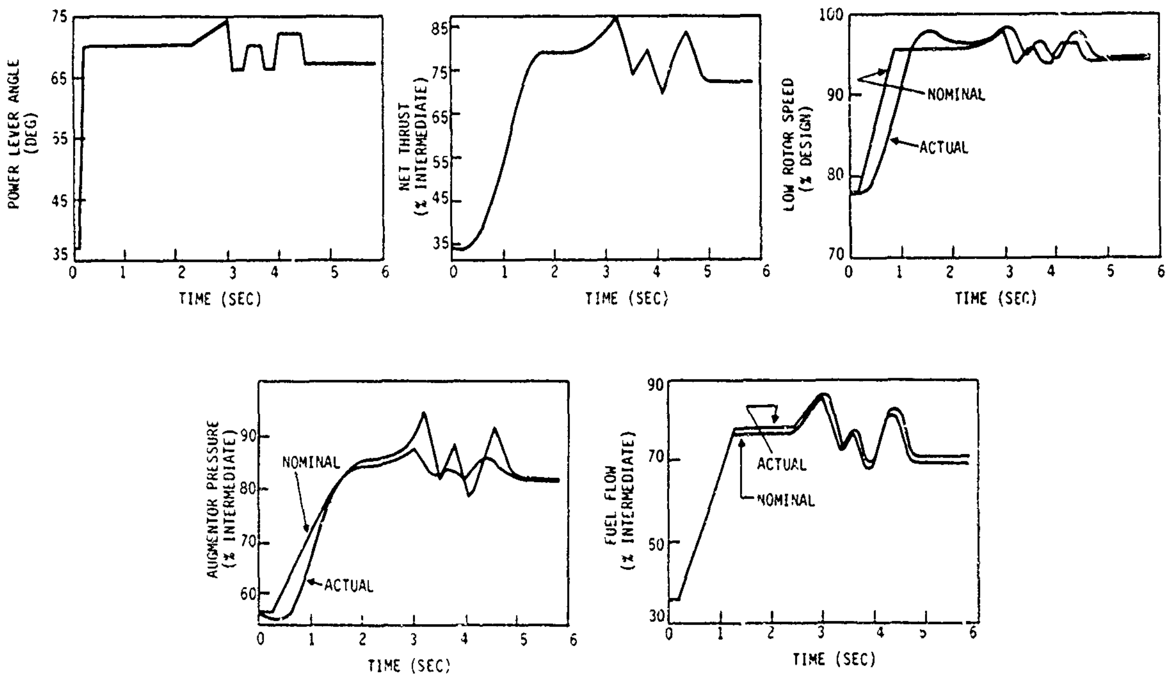

Figure 8 - Illustration of Transient Trajectory Generation Algorithm for Cyclic PLA Input at Sea Level Static Conditions from Nonlinear Digital Simulation.

Gain Schedule

The dynamic response of the engine is affected strongly by the air mass flow. Power level, altitude and Mach number determine this mass flow and the response. The linearized control synthesis (LQR) procedure produces regulator gains that control the engine satisfactorily in the neighborhood of the design flight/power point. To implement a continuous envelope-wide controller, the gains must be varied as the system makes the transition from one condition to another.

There is no precise analytical relationship between gains at neighboring linearization points. Although engine time constants can be modeled as functions of the ambient conditions, the performance index is chosen by the designer to satisfy specifications particular to the flight point. For example, a function of ambient variables will not correlate exactly the gain elements between sea level static idle conditions, where thrust stability is weighted heavily, and subsonic altitude idle, where burner pressure is the dominant state weight. The procedure adopted for the F100 implementation approximately fit important gain elements with univariate functions of the engine face density and rotor speed. The former variable accounts for altitude effects, while the latter schedules the power condition. Dominant gain elements are determined by assessing the closed-loop eigenvalue sensitivity of the system to each gain element (17) and eliminating those that do not affect closed-loop response. Over 50 percent of the scheduled control gains, C_x and C_y, were eliminated in the final implementation with little or no effect on system performance.

Integral Switching Logic

The design philosophy of aircraft turbine engines dictates that steady-state performance is obtained at various flight conditions when a particular physical limit is held exactly (see Figure 9). For example, sea level static take off thrust for the F100 is defined as the thrust obtained at the maximum allowable turbine inlet temperature. At lower power levels, the engine operation should cause the airflow and low rotor speed to attain predetermined values for optimum efficiency. At altitude conditions, the minimum burner pressure defines engine idle. Inlet airflow requirements and burner burst pressure determine operating conditions at some supersonic flight points.

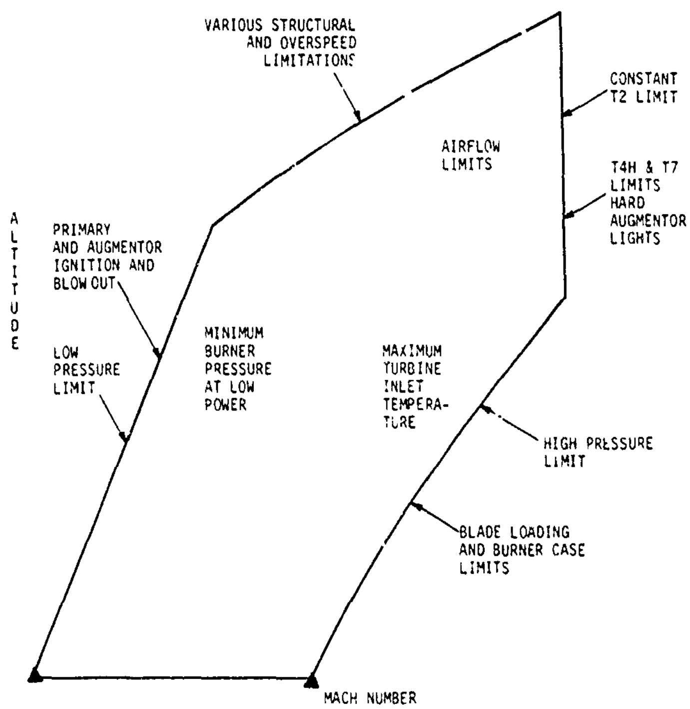

Figure 9 - Operating Envelope Constraint Limits for the F100 Turbofan Engine

The engine set-point is a group of reference values of states and controls which the engine must attain exactly in steady-state. These values define the equilibrium point. Since the F100 has set-point vectors whose elements change with flight and power conditions, a switching structure from trim control is required

Given the design model (Eq. 3) and the linear quadratic regulator design (Eq. 13), the closed-loop response to additive control inputs may be written as follows:

$$\dot{x} = (F + GC_x)\, x + Gu' \tag{24}$$

where

$$u = C_x x + u' \tag{25}$$

and u' is the additional control input. If the trim responses (i.e., the integral control time constants) are decoupled spectrally from the transient equations, i.e., time constants of Eq. 24, then the following should be approximately valid:

$$\dot{x} = 0 \tag{26}$$

$$x = -(F + GCx)^{-1}Gu' \tag{27}$$

$$y = [\ -(H + DC_x)(F + GC_x)^{-1}G + D]\ u' \tag{28}$$

or, $$y = H^*u' \tag{29}$$

The output vector y is chosen as m quantities, which must be held in steady-state to their reference values. (Controllability is assured, then, if H* is invertible.) The trim integrations provide system dynamics, namely,

$$\dot{b} = y \tag{30}$$

The control law is designed:

$$u' = C_y b \tag{31}$$

and the full controller i˜ ˊ ˋ ¬ented:

$$u = C_x x + \int C_y y dt \tag{32}$$

where elements of y and C_y can be switched arbitrarily while maintaining a continuous control time history.

The design of the control law C_y could be performed with a single application of the regulator synthesis procedure. However, because the elements of the y vector change according to limit conditions and control saturations, a complete design for all combinations of error vectors would require an extremely large number of C_y matrices stored in the controller.

The classical approach is to ignore various couplings in H*, and the integral control can be designed on a loop-by-loop basis. For each output,

$$\dot{b}_i = h_i^{*T} u' \tag{33}$$

if control weightings are chosen to represent the amount of control $u'_{j_{max}}$ which should be used to trim the outpu error y_i as follows:

$$B_{jj} = 1/(u_j)^2_{max} \tag{34}$$

then the optimal single-loop output regulator can be designed to place the spectrally separated trim root at $s = -\lambda$. The gain for this system is

$$C_{yi} = -\lambda B^{-1} h_i^* / h_i^{*T} B^{-1} h_i^* \tag{35}$$

The full gain matrix C_y is constructed as follows:

$$C_y = [C_{y1}\ \ C_{y2}\ \ \cdots\ \ C_{yr}] \tag{36}$$

where columns are chosen corresponding to the appropriate set-point and number of unsaturated controls. Equation 36 represents a single matrix that can accommodate any subset of output errors as long as a suitable set of actuators is available. The drawback of such a procedure is that the precise eigenvalue location of the trim root system is determined only approximately because of the neglected cross-couplings in Eq. 29. The problem can be minimized if the weightings are chosen (Eq. 34) such that each control is used primarily to modulate a single output error. The closed-loop eigensystem must be determined to verify suitable root locations for the trim and transient system combined. Further iterations may be required.

Alternately, if the closed-loop trim system

$$\dot{b} = H^*C_y b \tag{37}$$

is chosen such the H^*C_y is upper triangular, then any row and column of C_y can be deleted without altering the remaining closed-loop dynamics. Also, it is possible to replace a single row of Eq. 37 arbitrarily without affecting the remaining dynamics. The upper triangular structure and eigenvalue placement determined (m)(m + 1)/2 constraint equations. The remaining (m) (m - 1)/2 free elements of C_y can be chosen as zero, or a quadratic regulator construction in Eq. 35 can be used to resolve the ambiguity.

Either method just described produces a single m x r gain matrix, where r is the total number of possible output quantities. If l controls are saturated, m-l elements of the r output quantities can be chosen for trim. The control law then is implemented as in Eq. 32, with the l rows corresponding to the saturated actuators deleted from the matrix. The control is switched when an actuator saturates (delete a row and column), an engine limit must be accommodated (a column is replaced), or the error term associated with the saturated control will tend to unsaturate the control (add the row and column). The implementation produces an extremely simple structure for trim and transient control action which can accommodate various engine limits and control saturation, as well as obtain rated engine performance accurately throughout the envelope.

In the F100 implementation, the steady-state requirements are to have the compressor bleeds closed, vanes and stators tracking the optimum component efficiency schedules, and fuel flow and jet area adjusted to yield operating line performance without limit exceedence. Three elements of the set-point vector are the vane, stator and bleed schedules. These error terms always are integrated unless they are driven transiently into saturation. To avoid integrator wind-up due to this uncontrollable situation, the appropriate error is switched out until the transient command tends to cause the control to unsaturate. The remaining two elements of the set-point are normally, scheduled low rotor speed and an averaged fan exit total to static pressure difference $\Delta p/p$. The $\Delta p/p$ error term is eliminated if the jet area saturates. If burner pressure or turbine inlet temperature limits are reached, these terms are substituted for low rotor speed in the control law. The switching logic provides smooth and controlled engine transitions in power and flight condition.

Engine Protection

The engine protection logic in the multivariable control provides hard limits on the commands to the control actuators. The engine protection logic includes fuel flow limits, variable vane limits, bleed air limits and exhaust nozzle area limits. The fuel flow limits include the maximum and minimum fuel flow and an acceleration schedule, which is a function of measured compressor speed. Axial and cambered limits are imposed on the variable vane position. The maximum and minimum nozzle area limits are scheduled as a function of power lever angle. The maximum and minimum allowable area commands converge at idle power so as to prevent limit cycling in this operating region. Whenever a commanded actuator position exceeds a specified limit or when a control saturation is detected, a flag is set with the control logic. These flags send a signal within the logic to clamp and hold the appropriate trim integrator to prevent integrator wind-up.

FTIT Estimator

As specified by the manufacturer. temperature limiting during transient and steady-state operation is a critical function of any turbine engine control system.(3) For the F100, the maximum temperatures specified for compressor discharge and turbine inlet stations in the gas path are implicitly limited by the maximum fan turbine inlet temperature (FTIT). Accurate measurement of FTIT near the temperature limiting region, then, is absolutely necessary for successful engine control. Unfortunately, the FTIT sensor output response is extremely slow relative to the temperature overshoot criteria. Compensation of this signal is required for adequate temperature limiting during transient maneuvers. The compensation technique must not degrade the high d.c. accuracy of the signal because this measurement sets intermediate thrust at a majority of flight points.

A steady-state, third-order filter was designed. The FTIT "estimator" uses a combination of the sensed FTIT, the steady-state reference value of FTIT, the transition value of fuel flow and the commanded fuel flow to predict the final value of FTIT during a transient. The predicted FTIT is then compared to the maximum allowable FTIT. If the overtemperature is predicted, the fuel flow integrator begins downtrimming fuel flow before an actual overtemperature can occur.

The FTIT sensor output is attenuated at high frequencies within the filter. The steady-state gain of the estimator to the sensed input is unity, preserving the high d.c. accuracy of the measurement. The two fuel inputs are used to provide the initial high frequency response compensation of the sensed temperature. The estimator functions as a complementary filter in blending inputs of two types to form a system with acceptable response and accuracy.

An example of the performance of the estimator is shown in Figure 10. The overshoot occurs in advance of the actual FTIT response. This enables the controller to use the estimator output to modulate the controls to reduce actual temperature overshoots. Whenever an acceleration occurs that will not cause a temperature limit to be exceeded, the estimator output is not used to throttle back fuel flow. Thus, off-intermediate power accelerations are not penalized by the temperature limiting logic.

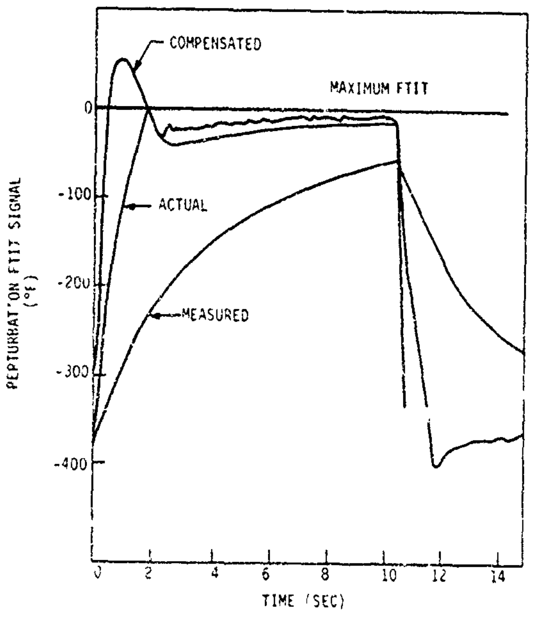

Figure 10 - Example of Temperature Compensation Showing Compensator Output Leading Both the Actual Temperature Response and Sensor Output During a 75% Thrust Step at 10,000 ft, Mach Number 0.9 from Hybrid Simulation.

Hybrid Evaluation Results

Initially, the control logic was validated on the F100 digital simulation.(18) During these tests, small transient responces were run to verify the steady-state regulatory performance. Large power lever transients were run to test the limit protection logic and the transition controller. Disturbances were generated to investigate the effects of augmentor ignition and inlet distortion. Utilizing the unique flexibility offered by the digital simulation, accelerations at sea level static conditions with severe engine deterioration and power extractions were done to test the control in this critical region. The digital evaluation provided a preliminary test of the logic at a limited set of flight conditions to validate the design and structure of the control logic.

The F100 multivariable control logic was then implemented on a SEL810B digital computer and evaluated on a hybrid computer simulation of the F100 engine(19) at the NASA Lewis Research Center. The SEL810B is a general purpose computer processor, and although not flight qualified hardware, its memory, speed and word size are believed to be representative of computers that will be used to control engines in the 1980's. Figure 11 is a schematic of the hybrid system. The primary objective of the hybrid evaluation was to verify the multivariable control logic and its implementation to ensure safe and stable operation of the F100 engine during subsequent altitude tests. The results of the evaluation indicated that the control logic and its implementation will be capable of controlling the engine throughout its operating range. The specified engine limits were not violated during normal steady-state and transient operation.

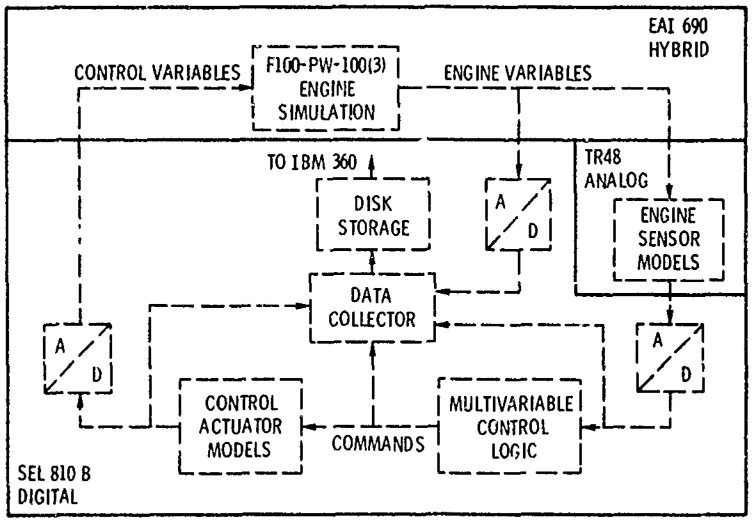

Figure 11 - Schematic Representation of the Multivariable Control Evaluation Configuration.

The evaluation flight condition (altitude/Mach number) and the types of tests conducted are listed in Table I. In all, 56 steady-state operating points were recorded and 77 transient tests were performed during the hybrid evaluation.

The multivariable control matched baseline, steady-state performance for all but a few supersonic test conditions. The degraded supersonic performance was attributed to reference point scheduling errors at those conditions. Minor modifications to the reference point schedules will produce satisfactory steady-state performance at all flight conditions. The proportional (LQR) plus integral control structure provided good fan operating point control and when required, tracked the engine limits.

The LQR and transition control produced satisfactory transient responses at most operating conditions. The specified response time requirements were satisfied for all small and large amplitude transients with the exception of the small (+3°) PLA snaps at the sea level/static, idle condition. A 1.2 second response time requirement for the small perturbations was adopted due to a lack of specificity in the design criteria.

The flexibility of the control structure and design methods was demonstrated by implementing a fast-acceleration set of rate limits in the transition control. The resulting sea level/static acceleration from idle to intermediate thrust in Figure 12 shows a reduction in the response time from 3.2 to 2.2 seconds.

The results of the sensor failure study at the 30 Kft/0.9 condition indicated that most sensor failures would result in a safe, downtrimming to a part-power condition. The saturation of the PT2 sensor or the loss of the fan speed sensor, however, resulted in an overspeed and overtemperature condition.

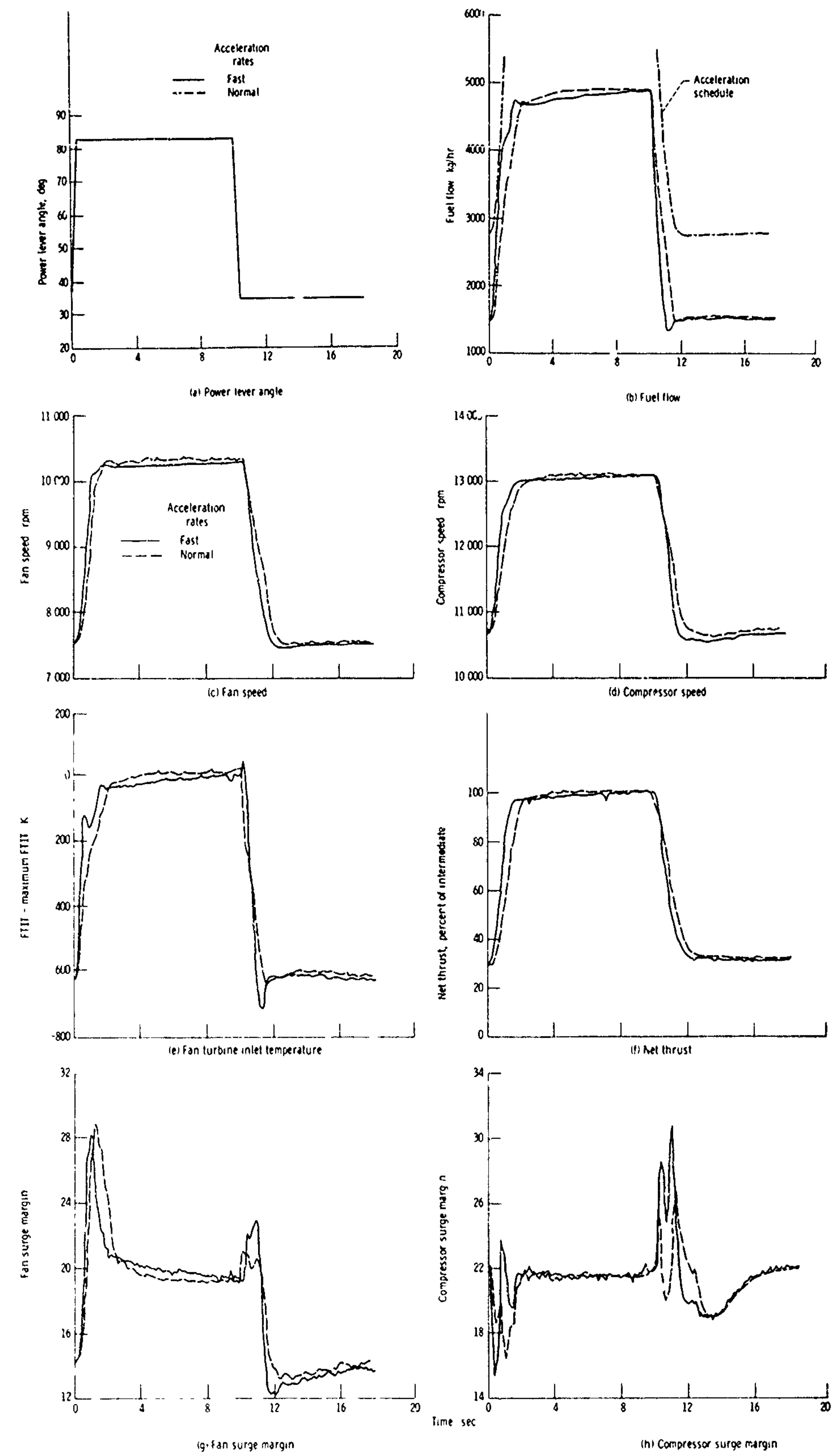

Figure 12 - Comparison of Normal and Fast F100 Simulation Responses to 35° to 83° Power Lever Angle (PLA) Snap at Sea Level, Static Conditions. Multivariable Control.

Therefore, a simplified sensor failure detection logic was implemented in the multivariable control prior to engine testing. MAX, MIN and delta checks were made against each sensor. These limits were determined using data gathered during the hybrid evaluation. Three consecutive "failure" conditions indicated a failed sensor. For noncritical sensors, the value from the reference point schedule was used instead of the failed channel. For failed PT2 and fan speed signals, the MVCS logic was disengaged and the engine power was cut back to a safe level.

Based on recommendations from NASA Lewis Research Center and from Pratt & Whitney engineers, the MVSC control logic was approved for engine test demonstration at NASA Lewis Research Center.

XD11 Engine Test Evaluation

Engine tests were run at five subsonic and four supersonic test points.(20) The flight conditions and the types of tests conducted are shown in Table I. In certain regions, air flow and burner pressure constraints limit the range of steady-state operation to near intermediate (PLA = 83%) operation. Transient control performance was evaluated by subjecting the control to small (3°) PLA steps, to large PLA snaps and chops, to random, cyclic PLA motion and to zone one afterburner lights. In addition, simulated flight maneuvers were performed during the engine tests.

ALTITUDE (FT) MACH NUMBER	STEADY STATE		POWER LEVER ANGLE PLA TRANSIENTS			DISTURBANCES		SENSOR FAILURES
	PLA = 83°	PLA < 83°	LARGE	SMALL	CYCLIC	AFTER-BURNER	MANEUVER OR FAST ACCEL	
0/0	●	●	●	●	●	●	●	
10/0.6	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	
10/0.9	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	▲
30/0.9	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	● ▲	
45/0.9	● ▲	● ▲	● ▲	● ▲	●	● ▲	●	●
50/0.9	● ▲	● ▲	● ▲	● ▲	●	● ▲	●	
65/0.9	●					●	●	
0/1.2	●	●	●	●		●	●	
10/1.2	● ▲	● ▲	● ▲	● ▲		●	●	
20/1.8	●					●	●	
55/1.8	▲					▲		
35/1.9	▲					▲		
75/1.9	●					●	●	
40/2.2	●					●		
55/2.2	▲					▲		
60/2.15	●					●	●	
65/2.5	●					●	●	

TABLE I

SUMMARY OF F100 MVCS HYBRID EVALUATION AND ALTITUDE TEST CONDITIONS

● HYBRID TEST

▲ ENGINE TEST

Prior to the MVCS tests, over 225 steady-state and 91 transient tests were recorded using the standard F100 control logic. These baseline tests were performed to record the XD11-8 engine's reference point values. Also, total and static pressure data at station 2.5 were recorded and used to synthesize the fan discharge $\Delta p/p$ parameters.

From these tests, it was found that engine XD11-8 differed significantly in operating characteristics from the nominal engine described by the digital simulation. Since the reference point schedules used in the MVCS control were based on simulation data, some adjustments were made to the reference point schedules prior to engine test. Also during the baseline tests, the MVCS limit mode switching logic and failure detection logic were thoroughly checked out.

Steady-state operating data were taken at 309 combinations of flight condition and power lever angle. The MVCS tracked the reference point schedules well. FTIT and four burner pressure limits were accommodated where required for safe operation. The integral trims held the RCVV's and CIVV's to their respective schedules. The fan rotor speed and fan discharge $\Delta p/p$ were held to their schedules values through the use of integral trims on exhaust nozzle area and main burner fuel flow.

In general, steady-state performance of the F100 MVCS control was good at all points tested. The integral control action held scheduled variables close to their scheduled values. Minor reference point schedule adjustments allowed schedule matching without controls saturating or engine variables exceeding allowable limits.

Transient performance was assessed at all the flight points. Large PLA transients were run at all points where air flow constraints permitted PLA operation below 83°. Small PLA transients of 3° were run to check the regulator performance while random PLA sequences were run to verify correct gain scheduling operation. In all cases, PLA was changed at a rate of $\pm$ 126°/sec. A programmable function generator was used to control the PLA during the transient tests to insure repeatability.

A total of 93 transients were run on multivariable control. A few which highlight key operational features of the control logic are presented here.

Figure 13 shows the response of the engine to a large PLA snap from 23° to 83° at flight point C (10000 ft; Mach 0.9). Several functions of the MVCS control are exercised with this transient: transfer from fan speed trim to FTIT trim, regulator and integrator gain scheduling as a function of compressor speed, FTIT estimation and the trimming of nozzle rea to set fan exit $\Delta p/p$. As can be seen in the figure, an idle to intermediate power lever step was initiated at around 0.5 seconds. The transition control generated requested value of states and controls. The regulator causes the sensed variables to track their scheduled values. The response is safe and stable with little or no overshoot. The FTIT estimator senses an FTIT limit exceedence at around 1 second. At this point, the fuel flow integrator input error was switched from fan speed to FTIT. The result is that fuel flow begins to cut back from the scheduled transition fuel flow. Notice that sensed fan speed, while being on schedule at the start of the transient, has fallen below its scheduled value and that FTIT is approaching its limit.

Initially, the nozzle area opened in response to the negative fan speed error. At time equals three seconds, the nozzle area begins closing to null out the negative tail pipe pressure P_6. The nozzle area integrator trim reduces nozzle area farther until $\Delta p/p$ is on schedule.

Afterburner lights were performed at all test points to investigate the ability of the MVCS control logic to attenuate external disturbance. Figure 14 shows the result of an afterburner light at 30,000 feet and Mach 0.9. As is shown in the top of Figure 14, a fuel pulse is initiated at time equals 0.5 second. Tail pipe pressure, P_6, rises sharply and the fan and core speeds fall off. Fan speed error causes the exhaust nozzle area to open bringing the sensed fan speed back toward the scheduled value. The exhaust nozzle area trim integrator further opens the nozzle until fan discharge $\Delta p/p$ is back on schedule. The MVCS control logic successfully suppressed afterburner pressure disturbances at all other flight points except for 45,000 and 50,000 feet, Mach 0.9. At these two points, sensed fan discharge $\Delta p/p$ did not change sufficiently to allow nozzle trim control to suppress the disturbance. As shown in Figure 14, the MVCS control logic far exceed expected results in meeting the design goals for afterburner suppression.

A total of nine simulated flight maneuvers were performed to test the control logic performance with varying PLA and flight conditions. These maneuvers included combinations of climbs, dives, accels and decels. The MVCS control logic performed well in all tests. Figure 15 shows one such maneuver. Here, an accel was performed at constant altitude (10,000 ft). Actual pressure altitude Mach number increased from 0.6 to 0.9 in about 15 seconds. Inlet temperatures could not be changed. The initial condition was standard day and the final condition is about 40°F colder than standard day. As shown in the figure, PLA is increased from 65° to 83° in about 5 seconds. The compressor speed transition was smooth with a slight overshoot. Fan speed tracked its scheduled value with also a slight overshoot. At about 4 seconds, the FTIT estimator reaches a limit and the fuel flow trim integrator uses trimming on fan speed error and begins downtrimming fuel flow to keep FTIT below its limit. The exhaust nozzle area close down to keep fan discharge $\Delta p/p$ on schedule.

During the altitude tests, alternate control trim modes were also run, demonstrating the flexibility of the control logic structure. One such mode was the EPR-N_1 trim mode where engine pressure ratio replaces fan discharge $\Delta p/p$ as the other variable used along with fan speed specify the fan operating line. The modular structure made it possible to easily change control modes. The EPR-N_1 mode required only new regulator and integrator gains to be entered. Under limited testing the EPR-N_1 control mode performed quite well. Another control change was the "fast accel" mode which was verified in the hybrid testing. Here the transition control rates were increased to obtain a more rapid than normal engine response. The modular structure of the control permitted this change to be made without changing regulator or integral gains, or the reference point schedules.

Also, the sensor and actuator failure detection and accommodation logic was tested at several flight points. In all cases, the engine transfer to a safe power condition was safe, smooth and orderly.

Conclusions

The objective of the F100 Multivariable Control Synthesis Program was to demonstrate that a control could be designed using linear quadratic regulator (LQR) design methods that would operate a modern turbofan engine over its entire flight envelope. The LQR design methods were used to develop feedback gains for a series of operating points. Reference schedules were used to translate pilot and ambient inputs to reference point specifications. A transition controller was used to produce smooth and rapid transitions from one operating point to another. A variable structure integral trim control was designed to produce specified steady-state performance and to accommodate limits. The performance of the multivariable control was evaluated on a real-time simulation of the P&W F100 turbofan engine with the control logic programmed on a digital computer. Use of the real-time simulation allowed program debugging and verification of proper control logic functioning prior to engine tests in an altitude facility. Sensor and actuator failure detection logic was developed and checked out by simulating transfers from multivariable to a backup control.

The multivariable control was tested while controlling an F100 engine at ten flight points in an altitude facility. The control exhibited good steady-state performance, i.e., the ability to hold engine trim variables on schedule at all flight points. Tests of the engine with BOM control prior to multivariable control tests provided data which were used to adjust some of the reference point schedules. This allowed tracking of reference point schedules without trim saturation and matching of engine operating lines obtained with BOM control.

Good transient performance was demonstrated at almost all flight points. The integral trims successfully accommodated FTIT limits and low burner pressure limits where required. The control attenuated afterburner pressure pulses occurring during afterburner lights at all but two flight points. At supersonic points, where operation was permitted only at intermediate and above, excellent suppression of afterburner disturbances was observed. The multivariable control successfully operated the engine for random PLA excursions, thereby verifying the correct functioning of regulator gain schedules and transition logic. A number of flight maneuvers were performed to check the control's performance with simultaneously varying PLA and ambient conditions. The control tracked reference point schedules well and accommodated all limits.

Programming flexibility which exists due to the modular structure of the multivariable control was demonstrated by testing two alternate control modes. A fast acceleration set of transition control rates was implemented which allowed more rapid engine accelerations. Also, the integral trim structure was changed to use engine pressure ratio instead of the fan discharge Mach number parameter normally used with the multivariable control. The new trim structure worked satisfactorily, requiring only a change of gain matrices to implement it.

Sensor and actuator failure detection logic was incorporated into the control for altitude tests and functioned well in conjunction with a backup control. All logic was programmed in 9.5K of core, using a 12 m.sec. computer cycle time. These computer requirements are within the capabilities of present generation computers envisioned for use as engine mounted digital controls.

It is concluded that LQR-based control design techniques can be successfully used to design digital engine controls. Its systematic, structured approach has much to offer in the design of controls for new generation airbreathing engines.

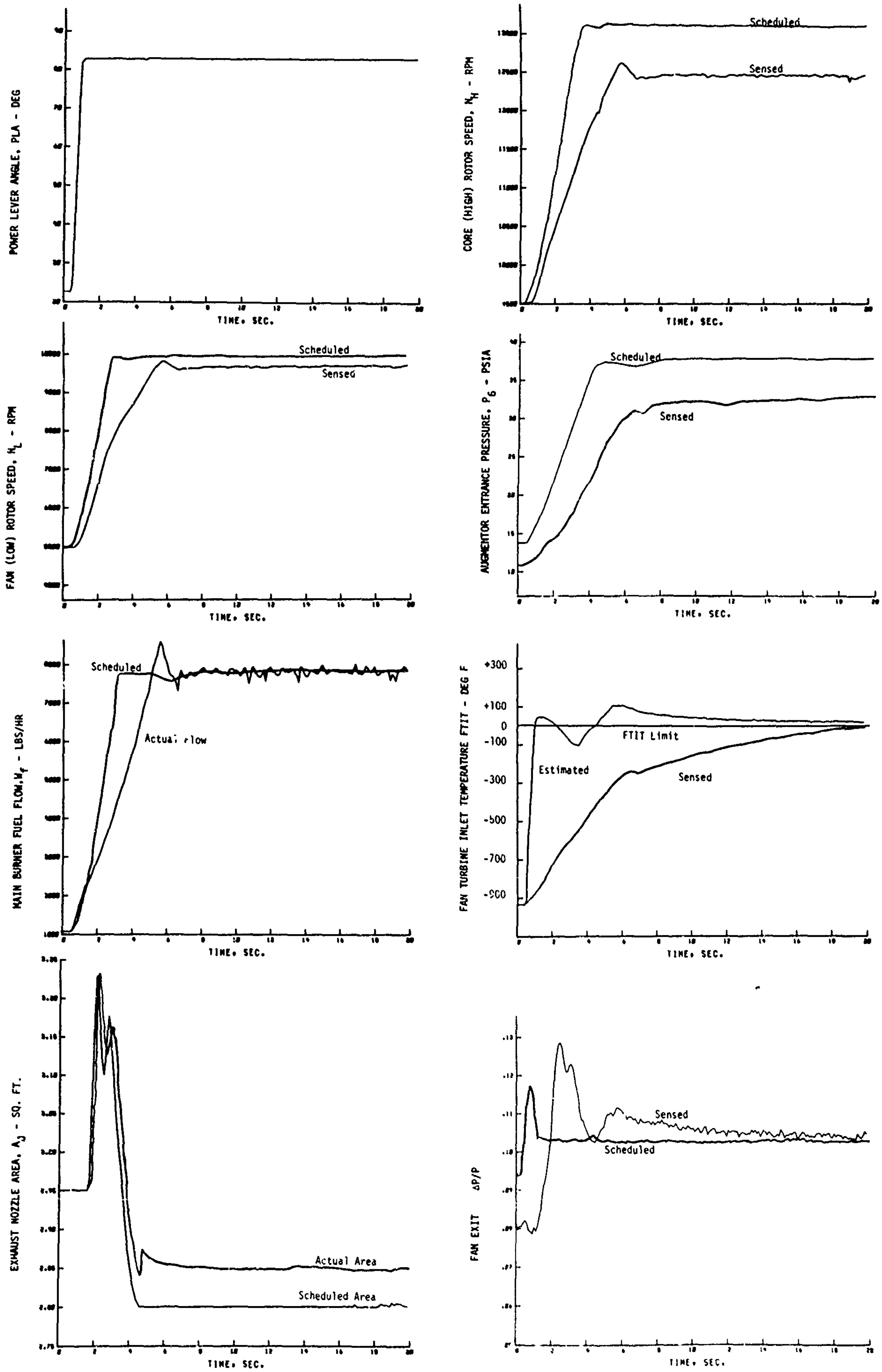

FIGURE 13 POWER LEVEL TRANSIENT 23° - 83°,
30,000 FT, 0.9 Mn

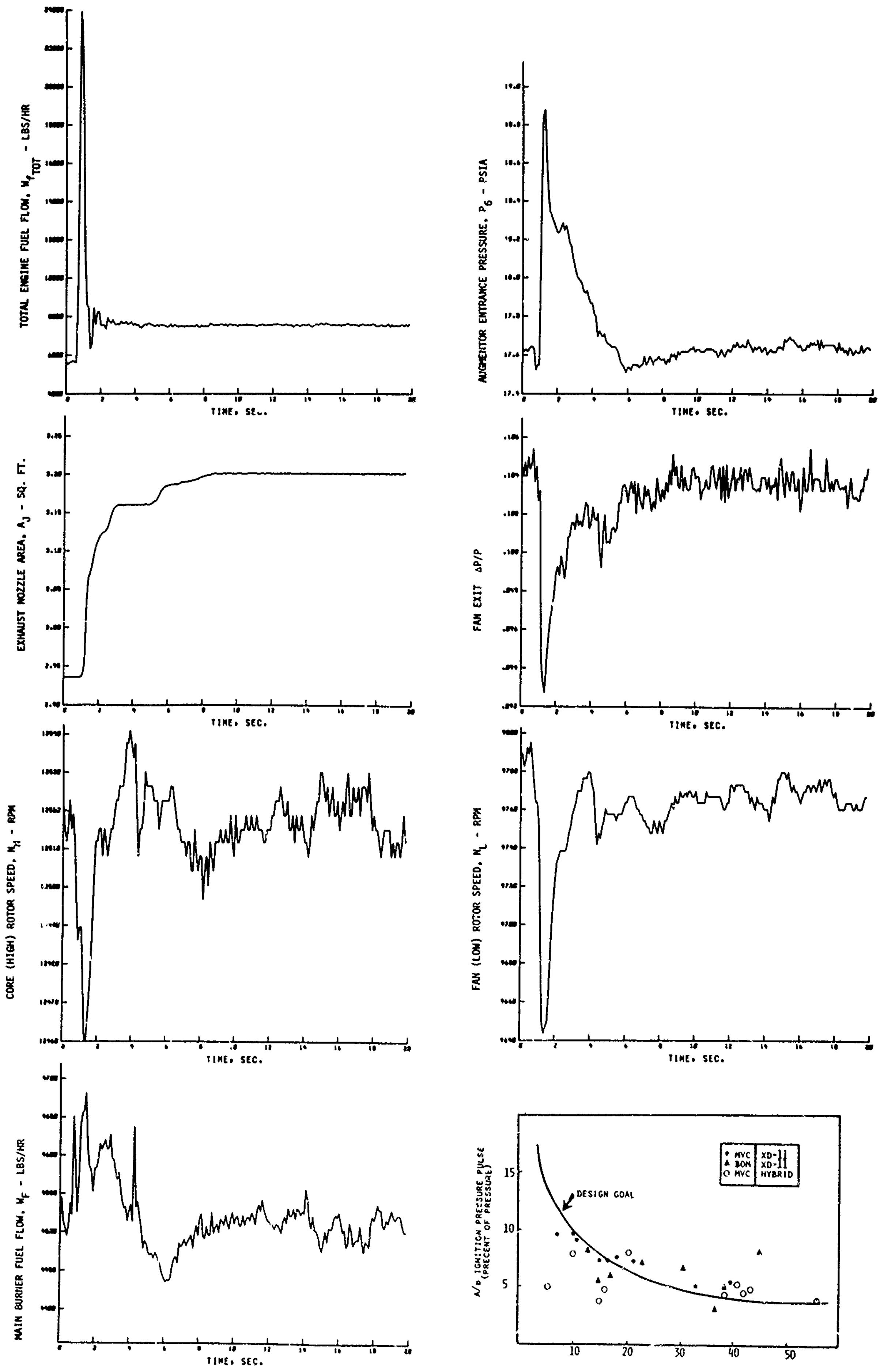

FIGURE 14 ZONE ONE AFTERBURNER LIGHT, 30,000 FT, 0.9 Mn

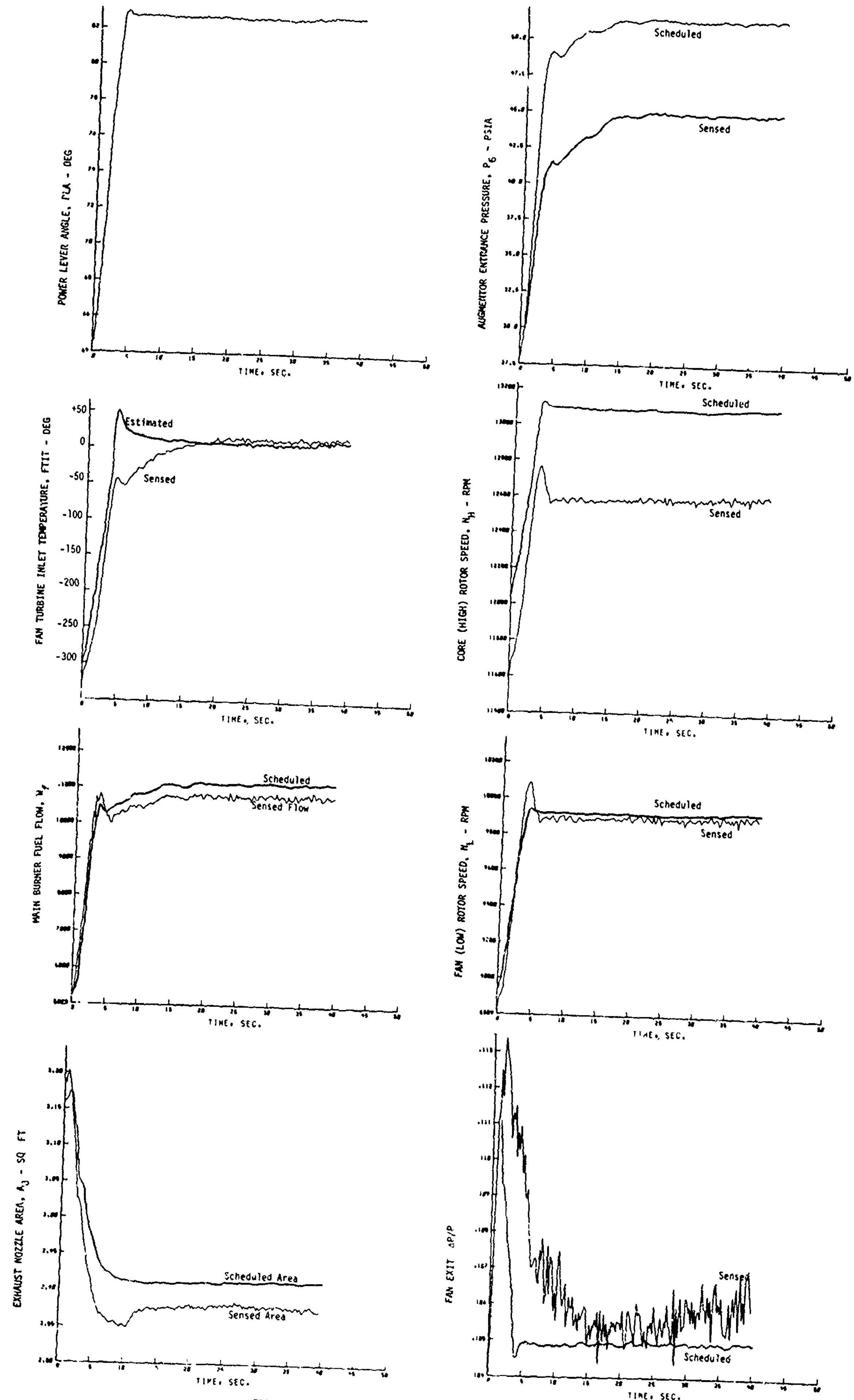

FIGURE 15 CONSTANT ALTITUDE FLIGHT MANEUVER
10,000 FT, 0.6 - 0.9 Mn, POWER LEVER
TRANSIENT 65°-83°

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DISCUSSION

M.P.Perks, UK

Temperature Measurement. The problems you experienced with temperature measurement are typical of transducer problems now seen. How necessary is it to go to the type of prediction technique you used, bearing in mind, that engine turbines themselves will respond even slower to temperatures of the gas path than the thermocouples

Author's Reply

Maximum compressor exit temperature and maximum burner temperatures are indirectly specified by FTIT limits by the engine manufacturers. Because of this and the fact that we would use currently available sensors, we chose to compensate the FTIT sensor. Perhaps the term estimator is inappropriate. The purpose of the FTIT compensation is to predict or lead the actual temperature in order that larger throttle transients will not lead to excessive temperature overshoots. The estimator output is used to trigger a switch in control modes in order to make safe transients and not as an estimator of air or blade temperature.

E.Roberts, UK

(1) What sample periods were used in the tests?

(2) Could reheat lightups have been missed because of sampling?

Author's Reply

(1) Our objectives in this effort concentrated on the ability of the modern control theory techniques to become a viable method upon which to base a control design. As a result we specified a sample time of 10 milliseconds in order that stability problems due to sampling too slowly would not be a problem. During the engine testing, we used a 12 millisecond up-date time.

(2) Because of our high sample rate and the fact that the afterburner pulses were of long duration, it is not likely that we may have missed them. The afterburner light offs were simply not severe enough to be sensed by our fan exit mach number probe. The F100 has a five zone augmentor and in our tests we lit only the first zone, so they were not full augmentor lights.

N.Munro, UK

(1) Have you been able to consider any of the modern multi-variable frequency-domain design methods developed in the UK and exposed at the NEC Chicago conference?

(2) Since you are obliged to use integral action in addition to the LQR controller, would you agree that a simpler design might have been achieved by a direct use of the frequency-response methods?

Author's Reply

(1) The program described in this paper began in 1976. Subsequently, the interest in multivariable control design techniques was spawned by this program and indeed, the theme problem for the NEC conference was the F100 engine represented by a linear model of the engine. Because of the success of our research using linear time domain techniques, we have continued to concentrate our efforts in this area.

(2) Actually, the LQR gains and integral trim gains represent only a small portion of the controller We chose to use integral trim control in order to achieve the precise steady state regulation specified by the engine manufacturer. The requirement to respect differing operating constraints throughout the flight envelope must be satisfied. The use of integral trim control allows for smooth transitions from one control mode to another Another advantage is that the integral action on one control variable has a minimal effect on the other variables

From my understanding of frequency domain methods, a set of control design gains for each operating condition where differing control requirements are to be satisfied must be done. I have not seen a frequency domain design that will accomplish a transition from a normal control mode to another mode in order to keep a variable below a specified limit, and do it with minimal switching interaction

Therefore, I cannot agree that a frequency domain design would have been simpler. It is difficult to compare techniques when they have not been used to solve the same problem

ENGINE INTAKE CONTROL DESIGN FOR ADVANCED FIGHTER AIRCRAFT

by

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SUMMARY

This paper reviews the factors influencing variable geometry intake design for fighter aircraft over their flight velocity profile.

Separate operating performance ranges, depending on the positions of the changeover valves, ramps and doors, are analyzed for an acceptable design compromise. A criterion for prediction of airframe integration effects on inlet stability with application to advanced fighter aircraft is presented and discussed.

To accomodate desired flow changes through the engine as flight speed, altitude and climatic conditions, change, the control of intake is studied and designed, taking into account mutual interferences between propulsion units and controlled elements.

Airframe/propulsion integration in fighter aircraft is considered in the design of intake control.

FIGHTER CLASSIFICATION AND OPERATIONAL PERFORMANCES

Tactics of future fighter aircraft has to be improved, and in particular pilots have to be assisted in the execution of complex tactical maneuvers, in order to obtain superior combat capability. In the field of avionic development, the future technology, for the application of the ever widening range of sensors together with the associated data processing and control systems, seems almost limitless.

Fighter performance includes the capability to generate forces which allow a transition from one flight condition to another. Combat maneuvers nearly always take place at high speeds in a relatively small airspace and therefore it is interesting to consider the performance level required in relation to the air space available. Required load factors, bank angles and power settings, are dependent on the type of fighter aircraft mission: interception, air combat, ground attack.
Turning performance is not predominant in the interceptor fighter, requiring high speed and high longitudinal acceleration toward a non-manoeuvring target, and there is little need to consider low speed combat. The aerodynamic configuration is characterized by low profile and wave drags.
Airfield performance is important in the air combat fighter, at low or medium altitude, and the highest supersonic speeds are not necessarily required. The bes possible sustained and istantaneous turning performance is essential. From the aerodynamic point of view, low induced drag at high "g" and good departure characteristics as the dynamic stall is approached, are required.
High wing loading is desirable, for improving the ride quality and aiming accuracy in respect to the target in conditions of rough air, in the medium-range air-to surface attack airplane (ground fighter). The wing loading is much higher than for the other fighter types. There is no need for supersonic performance and high turning performance. An acceptable compromise between the overall aerodynamic efficiency, on the way to the target, and the high drag rise Mach number and the store carriage arrangement, is characterizing the aerodynamic design.

For compromising the ideal characteristics of two of the three fighter types, the engine development is no more centered around fixed cycle, afterburning turbofan engines, but around variable geometry and multicycle engines. The design condition is predominantly at high subsonic speeds, for tight combat turns and high rates of climb. Here the engine is used in full afterburning mode, with the transonic cruise legs performed at maximum dry power. Engine requirements for the interceptor fighter in supersonic flight result in higher compressor pressure ratios, some what higher fan by-pass ratios, and more sophisticated variable geometry air intakes and ejector nozzles.
Even though with some difficulties for the compromise, the MRCA Tornado might be regarded as lying along, the side joining air-to-surface attack and interceptor, while the F-15 would lie more nearly on the line joning interceptor and air combat fighters.
Those aircraft substantially designed air-to-surface attack have higher wing loadings than those designed for air combat, with the interceptor generally intermediate: F-14B (2.50 - 7.28 aspect ratio; 489 kJ/m^2, take off weight, and 4.3 kJ/m^2, combat weight, wing loading); as compared to F-15 (3.0 aspect ratio; 3.02 kJ/m^2, take off weight, and 2.78 kJ/m^2, combat weight, wing loading). A practical limit for fixed wing aircraft is a combination of 2.87 kJ/m^2 wing loading at combat weight, anf aspect ratio of around 3.5.
The F-14B shows the powerful effect of variable sweep, to compensate for the high wing loading; in fact, the span loading parameter is 1.96 kJ/m^2 at take off weight, 1.72 kJ/m^2 at combat weight wing swept, and 0.6 kJ/m^2 at combat weight with wing spread.
The delta design combines its moderate wing loading with the highest of the span loading.

With the aid of the computer and the simulation of air combat, a search is started to determine the parameters which best characterize the future fighter aircraft A measure of maneouvrability was given by

the area of the diagram between the specific excess power (S.E.P. = (T-D)•V/W) against sustained turn-rate at given Mach number and altitude. S.E.P. is regarded as one measure of combat capability and is equivalent to steady rate climb. The boundaries of sustained capability of an aircraft embracing maximum speed, ceiling either at 1 g or when manoeuvering, are all obtained when S.E.P. is equal to zero. But, since S.E.P. is proportional to longitudinal acceleration and turn rate is about proportional to normal acceleration, a more useful diagram results by plotting the two accelerations against each other. In such a way, we have diagrams corresponding to the envelope of the resultant acceleration vector of the aircraft; e.g. at a given sea level Mach number, from airbrake to maximum thrust, considering the effect of extra lift and thrust or the effect of variable sweep wing and vectored thrust. With structural design limits of + 8 and - 4 g, as values of the normal acceleration, the pilot, flying in stabilized flight, may ask maximum longitudinal acceleration by opening the throttle and selecting reheat, going in a few seconds to the maximum normal acceleration rolling the aircraft through substantially 90°. In the next generation, we need less than 2 to 5 seconds engine acceleration times, fast operating airbrakes, and very high rates of roll and pitch.

Although the pilot controls load factor and bank angle, the standard cockpit instrumentation is not adequate to permit him to fly consciously a pre-determined control schedule. A limited number of key points defines the shape of the maneuver in the initial phase, since the target most probably has not yet been acquired. The pilot has some time available to look the instrumental information, but it is impossible to make in practice usable estimates of these data, leading to the desired weapon delivery conditions. In a number of cases the actual execution of combat maneuvers does not lead to the desired flight conditions, so that its effectiveness is degraded. The parameters that affect the flight are related to the performance characteristics of the fighter. The relative flight control system is normally associated with undesirable complexity, for the very high number of parameters which affect the flight path. This complexity may be minimized by a parametric simulation during the pre-hardware design phase for longitudinal, lateral and directional control, to realize an adequate automatic flight control system.

For a ground fighter, as an example, a possible primary and alternate mission profile is shown in figure 1, Ref. 1. Such a vehicle would be expected to operate a large percentage of its life at dry supersonic near 12 - 15 000 m altitude and at speeds in the neighborhood of Mach 1.6 - 2.0, depending on engine availability for dry supersonic operation. At maximum dry thrust, the fuel consumption may already be twice that at the clean cruise and, for the later designs, the fuel flow at maximum reheat may be multiplied by a further factor of 5 or 6.
The dry and reheated thrusts at M = 0.8 sea level, expressed as thrust/weight ratio, for aircraft with full internal fuel and missiles, are, respectively: F-14B (0.6, 1.35), F-15 (0.58, 1.33), F-18L (0.62, 1.4), F-16 (0.5, 1.5), F-4K(0 45, 0.95), MIG 21K (0.52, 0.85).
This means that the combat time in full reheat is measured in minutes, considering a fuel supply for an hour of clean cruise at low altitude.

More development has to be placed in the area of aerodynamics, stability and control, and propulsion, to achieve the desired fighter performance objectives.
Variable-camber wing, automatically programmed as a function of Mach number and angle of attack, may increase the sustained-maneuver L/D. A weight reduction, in favour of volumetric efficiency, overall size and cost, is obtained by wing-body blending adoption. The use of blending permits greater flexibility in tailoring the area distribution curve, providing a better wetted - area - to volume ratio. The controlled vortex principle in highly swept delta wing configurations permits to achieve the proper balance between aerodynamic performance, stability and control. The use of the fly - by - wire control system provides the flying qualities to utilize the advances in aircraft aerodynamics and propulsion systems. The aircraft's flight control has no mechanical connection between the pilot control and the control surfaces. The relaxed static stability aspect of control configured vehicle technology is adopted to increase the maneuvering performance. The instability at subsonic speeds, including gust effects is well governed by control power.

The inlet location is selected to meet the high - maneuver - performance requirements, to provide a good area distribution, and to produce low distortion and turbulence at the compressor face. The normal-shock design, simple and low cost configuration, represents a compromise to the maximum speed performance in combat regime. The fixed - geometry design is lighter than a complete variable - geometry inlet planned for optimum performance over the structural design Mach/altitude envelope of the airframe.

As the functional requirements of the flight control system increase, and as the mission reliability and safety requirements dictate the need for redundant systems, digital mechanization of the flight control electronics is preferred. The advantage of digital flight control systems, when compared with analog systems, have been attributed largely to the stored program increased computational accuracy and flexibility. However, the software associated with this flexibility represents a new element in the flight control system design process, requiring specification and development. Advantages of the digital mechanization are, essentially, superior capability of the digital computer to execute logic functions, and improvement of flying qualities by using control laws not feasible with analog systems.

The now available new techniques for the design of the control and stabilization systems lead to a remarkable improvement of the expected mission effectiveness and to the innovation of new modes of operation.

DEVELOPMENTS IN CONTROL SYSTEMS FOR VARIABLE GEOMETRY FIGHTER POWERPLANTS

Engines of much higher specific thrust than the conventional turbo-fans have to be used for the wide flight envelope of high performance fighters. There is a growing tendency to prefer twin engine installations. In these cases, the empty airplane weight penalty may be less than 9%. This is due in large part because the airframe structure grows and there are additional problems to optimize the afterbody design for low transonic drag, both with and without afterburner.
Although the by-pass principle is commonly used, by-pass ratios are generally around unity or lower. The by-pass and core engine flows are generally remixed in the jet pipe to feed a single propelling nozzle. Jet pipe reheat is normally used to provide the large thrust boost needed for supersonic flight; but there is considerable interest, at some flight conditions, on attaining the greatest possible thrust with reheat unlit (e.g., the very low altitude penetration to the target on a strike mission, requiring flight at a high speed with good fuel economy).

The maximum dry thrust available tends to be the factor which limits flight speed. This is the reason because design is concetrated on the technique of supercharging the core engine. The problem is to define efficient dry-power engines for supersonic cruise, that would satisfy transonic acceleration and subsonic requirements. Variable geometries and cycles provide increase in air flow as well as pressure ratio, to produce efficient matching for a variety of operating conditions, especially if efficient sustained supersonic cruise is desired.
By-pass engines may by adapted to multi-mission fighter capability.
For the ground fighter, variable cycle engines, which provide air-flow variation through variable turbine area and variable nozzles and compressor stator blades, in combination with high throttle ratio, may have different solutions, all based on the by-pass principle: mixed burning stream (with variable geometry fans and compressors, and conventional control); high throttle ratio (with increased air-flow control, and variable area turbines); duct burning (with increased air-flow control, adjustable nozzles, and variable compressors); variable pressure ratio (with pressure ratio control, by-pass ratio control, and adjustable nozzles); rear valved (with pressure ratio control, by-pass ratio control, and adjustable nozzles). By-pass ratio may range from 0.2 to 1.3, and pressure ratio from 15 to 20 or more.
Figure 2 shows a two-shaft low by-pass ratio powerplant. Variable cycle features for thrust boosting are indicated. The increase of low pressure ratio for higher thrust is applied to the fan as a whole, thus raising by-pass pressure as well as core entry pressure. The application of the core supercharging principle for increasing the thrust, does not increase the turbine entry temperature, even though a relatively small raise in high pressure rotor speed is obtained.

The interest in engines with a variable thermodynamic cycle is extended to fighter aircraft, because of: favourable specific fuel consumption, in supersonic and subsonic flight, with or without reheat, and thrust characteristics; optimum engine integration and handling qualities; high maximum dry thrust, related to maximum reheated thrust; high aerodynamic stability on afterburner light up; optimum matching of intake capacity and engine mass flow; good compatibility with intake distortions; favourable afterbody/nozzle aerodynamics; low effect of bleed/power off-take on engine performance and stability; acceptable weight and cost.

Considering the by-pass principle, in which downstream of the fan the total airflow is divided between an outer fan duct and the central core engine. the variable cycle concept may be realized as follows, Ref. 2:

- the turbines and the internal flaps in the exhaust system can be given settings to provide a turbofan operating with two or three streams. For supersonic cruise flight, with two streams, the second one is not burning in the duct. This stream is burning for take-off, climbing and transonic acceleration. Operation on three streams without duct burning is used for subsonic cruise flight;

- when low thrust is required, in subsonic cruise flight, the high pressure - system runs with high output, the entire engine working as a turbofan with duct burning shut-off. When high thrust is required, the high pressure system is throttled, while duct burning is on at high temperature, working as a turbojet. Modulation, throttling, and appropriate harmonization of the burning temperature, consent intermediate operations;

- the by-pass ratio may be modified by the variable high and low pressure turbines and internal flaps, having high thrust (with or without duct burning) at low by-pass setting, and higher by-pass ratio for subsonic cruise;

- the variable turbofan provides, through variable splitter, intermediate and low pressure turbines, primary and secondary nozzles, a considerable range of by-pass ratios by keeping the two streams separated. The engine works in reheat operation with a by-pass ratio equal to zero. The afterburner cooling air taken off down-stream of the intermediate compressor is throttled as in the case of the variable turbojet;

- the variable turbojet, with variable turbines and final nozzle, provides optimum pre-requisites in connection with the afterburner, to be cooled by compressed air which is throttled, preventing reaction on the compressor.

The effectiveness of a multi-role combat fighter requires an engine concept that combines the advantages of the reheated turbojet; i.e. favourable ratio of dry thrust to thrust with reheat, good specific

fuel consumption with reheat, excellent stability and handling qualities in connection with the afterburner, intake mass flow flexibility, acceptable compatibility with inlet distortion, good flow conditions to reduce afterbody drag, and maneuverable control system.
All this may be at present obtained with variable geometry of the engine in several components.

A variable cycle engine must have the ability to make significant changes to its thermodynamic cycle, at a particular thrust and flight condition, without incurring a performance and weight penalty which would cancel the value of variability. The variable geometry components offer advantages as regard the flexibility of the propulsion system, but it becomes mandatory to have an efficient control to reduce in time the unsteady flow originated and pressure waves travelling up and downstream along the engine.

Supersonic V/STOL fighters require propulsion systems which produce thrust well in excess of aircraft weight. The powered lift requirements, plus the flight performance requirements of the fighter mission, result in extensive compromise in variable cycle and geometry for obtaining efficient fuel utilization at both supersonic and subsonic conditions, high thrust for combat, good airframe integration characteristics, rapid thrust response for hover, high bleed rates for control.
The intercept mission emphasizes high power performance for vertical take-off, maximum power climb, supersonic dash, and supersonic combat. The subsonic surface surveillance mission emphasizes low power fuel utilization efficiency in the long range subsonic cruise out and back, and long loiter on station. Future V.STOL fighters require high specific thrust (afterburning) engines to best include multimission objectives for transonic/supersonic cruise and combat and subsonic loiter. As subsonic and supersonic combat specific power levels increase, variable geometry exhaust systems are required for a wide range of cruise/acceleration and maneuverability transient conditions. Exhaust systems capable of deflecting or turning the exhaust gas to achieve vertical and short take off and landing, require an external variable area to provide a maximum efficiency thrust vectoring system, by utilizing a variable aft expansion ramp for a range of upward or downward vertical thrust components.

The engine generates external forces that affect the drag and lift of the airplane. The drag production is due to either viscous losses and shock losses. The engine induce large pressure variations in the region in front of the engine and behind the engine that influences the aerodynamic properties of the airplane, including lift and pitching moments. In the front we have sinks that accelerate the flow; the interference between engine flow and external flows extends downstream of the engine. From the other hand, the effct of the flow-field produced by the airplane on the engine performance is strong for engines imbedded in the fuselage, as normally for fighters. For flight control purpose, the aero/propulsion forces on aircraft have to be accounted, to ensure that the performance predicted for each of the various elements (i.e., inlet, exhaust system airframe, and turbomachinery) are properly integrated to permit an adequate flight control.

The complexity of fighter powerplant control requirements, particularly at the reheat end of the system, is the primary reason for choosing a digital system in engine control. The primary purpose of the propulsion control system is to operate the engine and inlet within known mechanical and aerodynamic limits, while providing the desired thrust performance during all flight conditions at minimum level of fuel consumption. Recently, diagnostic functions have been added to determine engine condition and necessary maintenance actions.
Variable geometry engines require extensive integration and more sensing computation and actuation functions, with electronic control. Based on the general trend toward more extensive use of digital systems, the future fighter aircraft will be flown almost entirely by an integrated avionic system. In this approach, all the subsystem functions, such as guidance, flight control, communications, displays, weapon delivery, and propulsion control, will be combined in a central micro-processing unit. The common link between the central processor and all the subsystems will be a digital data bus, with all computations highly automated according to the performance requirements, Ref. 3.

FACTORS INFLUENCING VARIABLE GEOMETRY INTAKE DESIGN FOR FIGHTER AIRCRAFT

In the case of variable geometry supersonic intake, the design must be a compromise approaching the optimum flow to the engine, with minimum efficiency loss and drag increase in the flight speed range.
In respect to the fixed inlet, figure 3, the two dimensional variable inlet has, for example, horizontal ramps (three compression ramps and a diffuser ramp), figure 4, and may have diverter, translating spike, hinged lower cowl lip, to provide a uniform inlet flow-field at high angle of attack at supersonic speed, and to avoid engine surging and blade vibration.

Because of shock waves, friction and flow separation, the intake pressure recovery, defined as engine face mean total pressure/total pressure achieved in adiabatic isoentropic compression, is less than unity. The momentum lost approaching intake is the spillage drag, due to the diverted excess flow. Some of this lost moment may be recovered by the cowl suction. Other intake drags are due to boundary layer bleed, by-pass, environmental control system, and waves.

External compression inlets when aircraft missions require extended flight at Mach number in the 2.0 to 3.0 range, external compression inlet applications become less desirable in spite of their inherent stability and simplicity, figure 5. At Mach number 3.0, for example, a typical two - dimensional external compression inlet might have a final compression ramp angle of about 40°, with a cowl lip angle of approximately 25° to 30°. The cowl drag which results from this high lip angle can more than offset the pressure recovery potential of the design. In this case, figures 5 and 6, the geometrical configuration of the air

intake is approaching an isentropic compression ramp, according the Prandtl - Meyer theory. The ramp profile realizes an "infinite" summation of small pressure increase Δp, a condition for which the highest pressure recovery is reached. The choice of a typical isentropic compression ramp depends upon this advantage, figure 7. For a given inlet diameter, we have obtained, figure 8, contours and focuses of isoentropic ramps, for M = 2.0, 2.5 and 3.0. The air intake is two - dimensional, as flow and cross - sectional area, up to critical conditions, after which is undergoing gradual modification in the relatively long subsonic duct, reaching the front engine circular section. At M = 2.15, the focus coincides with the air intake inferior cowl lip, so that, the configuration is characterized by: a compression wave interesting a constant angle segment 0 C, another compression wave along the isoentropic profile, and a normal compression wave at the critical cross section, where the subsonic duct is starting.

This simple air intake configuration is adapted to other flight Mach numbers. As in the two dimensional inlet of figure 9, where a small amplitude compression wave system is determining an external supersonic compression air intake, both ramps are hinged in one or more points, and the intermediate boundary layer bleed is variable, to make possible an acceptable operation in a range of flight Mach numbers. In figure 10, an air intake for M = 2.5 and 70 000 N dry thrust engine is represented. The isoentropic ramp is followed by a boundary layer bleed and a second ramp; a schematic nozzle control is indicated at the engine exhaust. A, B and C, are the ramp hinge points. It may be observed on figure 11 that configurations more or less close to the ideal required conditions are deduced by rotating the first ramp around the hinge points A and C. It is obvious that this accomodation is happening with high energetic losses, in other words, with less pressure recovery. On figure 11, it is also indicated the hinge point B, around which the second ramp is rotating. Another problem emerging from figure 8 is regarding focus position. Each ramp has its own focus; and focus - inlet cowl lip coincidence is the condition of best operation, in other words, a more regular pressure recovery as shown in figure 12, Ref. 10. Here, the flow is critical at that point, at which the pressure recovery is a maximum for maximum absolute airflow W. This condition is normally characterized by normal shock location at, but just inside, the cowl lips. When the normal shock moves ahead of the cowl, the absolute mass - flow rate is reduced while the pressure recovery is depending on the inlet design. As it is known, this entire region of reduced mass flow is called the subcritical region. Conversely, the normal shock may be drawn down into the diffuser passage, causing a reduction in pressure recovery but no increase in absolute airflow rate above the critical value, i.e., the known supercritical operation. Referring to figure 8, subcritical, critical and supercritical conditions, are respectively for M = 2.0, 2.5 and 3.0. It is possible to obtain the optimum condition for an air intake, when the required engine weight flows, corresponding to various flight speeds and altitudes, and the secondary and main flow distribution, are known. Referring to these data, increasing and decreasing air flows, with corresponding secondary flow control, are obtained through ramp rotations around the hinge points A and B for a variation of bleed capture cross section. A more sensitive flow control is obtainable with a bleed door, figure 10. Using a variable geometry scheme, the entrance region is changing in such a way that the correct stream tube is captured for each flight Mach number and value of the static temperature. In this case, it is convenient to install the inlet in a region where the local Mach number is lower than the free stream Mach number. The variation of inlet geometry can be designed to produce variations of A_o and A_{min}, figure 13, Ref. 11. A_{min} fixes the transition from supersonic to subsonic flow. The external compression axisymmetric inlet is shown in figure 14, with a continuous compression. Conditions may be tranlated to mixed, external and internal compression with variable geometry and spike translation.

The air flow is slowing down on the subsonic duct, depending, figure 10 and 15 on the conditions established by the front ramp and the following bleed chamber. The relative pressure is also function of the air going through the bleed, so that the diffuser geometry depends upon this parameter, as it is seen in figure 16 for subsonic and supersonic flow. The relative geometrical characteristics are represented on figure 17. In the section downstream of the first ramp, the open door following the supersonic profile is determining a slip brutal deviation for the pressure increase from supersonic to subsonic regime. The boundary layer separation is avoided by air-breathing through the bleed fissure. Bleed operation is represented on figure 15, where ε, ε_b, η_o and η, are, respectively, internal flow coefficient, bleed flow coefficient, bleed efficiency, and air intake efficiency.

The intake drag in supersonic flight exerts a significant influence. It can be regarded, figure 18, as having two components: that which arises from the deflection of air through the shock wave system upstream of the intake lips, and that stemming from the positive pressure on such forward facing surfaces of the intake. The relative total drag is varying as the intake geometry is changed.

Various types of external compression axisymmetric inlets are illustrated on figure 19. Ferri, Refs. 13 and 14, did a great deal research on all external compression inlets. Although the total - external compression inlets. Although the total - pressure losses of external compression inlets decrease as the number of oblique shocks, figure 20, Ref. 10, is increased, it has been found in practice that the use of more than two shocks offers greater flow complication. In the completely "isentropic" compression, figure 10, an oblique shock of finite amplitude is initially generated by the sharpest practical leading edge and the subsequent compression is isentropic. In this type of compression, a compression limitation exists, as shown on figure 19. The static pressure rise across the strong shock must equal the rise through the isentropic zone and reflected wave and thus balance across the vortex sheet, Ref. 15. The maximum isentropic and theoretical normal shock and two and three shock external compression inlets recoveries are presented in figure 20. Instabilities is normally ascribed either to the entering shear plane, after Ferri, figure 21, or to shock wave-boundary layer interaction leading to flow separation on the supersonic compression surface, figure 22. But, many other variables are thought to significantly af-

fect instability phenomena. Some intakes of recent concern exibits two phase of instability. After a small reduction in mass flow, a low amplitude oscillation, the so-called "little" buzz, suddenly appears, while further throttling iniziates "big" buzz. The latter is of much larger amplitude than little buzz, although the frequency is similar. A large stable sub-critical margin tends to imply a high pre-entry drag, figure 23. The basic principle is to devise, Ref. 10, a range of intake geometries such that as many as possible of the factors thought to influence instability phenomena remains constant, varying in a systematic manner the supersonic compression field, through ramps, in terms of the total pressure gradient falling across the cowl lip and of the deliberate employment of particular combinations of shocks.
Computer programs for calculating the flow field in three dimensional axisymmetric or two-dimensional inlets have been prepared. A program limited to applications in which the bow shock wave does not intersect the cowl, so that internal shock wave intersections do not occur, is presented in Ref. 16. In order to facilitate the computation, the flow field behind the shock wave is broken into several regions bounded by shock waves, as shown in figure 24. The standard procedure adopted is the method of characteristics.
At supersonic flight speeds, an important operating mode of an air intake is the mode in which the terminal shock occurs ahead of the cowl lip of the diffuser. The compression shock can be the result of different causes, such as flow throttling by the engine, insufficient throat area, or change of flow direction at the cowl lip by a turning angle greater than critical. At the stagnation surface, the flow pattern becomes complex because of interaction between the shock wave and the boundary layer, and flow separation zones are produced.

External compression with variable geometry inlet - The concept in figures 4 and 5, relative to the F-15 inlet provides an external compression, with a system of three oblique and one normal shock ahead of the cowl, Refs. 5, 6 and 7. Boundary-layer bleed is provided through porous regions on the second and third ramps (15%), through the throat slot (70%), and through the side plates (15%). The bleed is exhausted on top of the inlet. A by-pass system is included for inlet-engine matching at different speeds and altitudes. By rotating the entire forward ramp, the capture area is changed.
Fixed and variable capture area inlets were tested in the F-15 program. The benefits of the relative shock system behaviour, as it influences inlet total pressure recovery and instantaneous total pressure distortion, are depicted in figure 25. The shape of inlet sideplates was investigated to determine the effect on inlet behaviour. Blunt lip shapes of the lower cowl were tested for improving recovery and distortion and delaying lip separation at high angles of attack at subsonic speeds.

The F-15 movable inlet ramps and air by-pass door are controlled by an electronic computer and hydraulically operated actuators. The computer receives signals from sensors that measure flow-field conditions ahead and within the inlet and provides signals to the three actuators that set the ramps and by-pass door to their proper position, figure 26.
More in general, the geometry of inlet is variable, through mixed-compression systems, to provide adequate transonic airflow to satisfy the engine airflow demand.

Improvements in electronic-control technology is providing reliable control systems to meet turbine engine requirements, including increased accuracy, multiple control loops, and more communication links between the propulsion systems. Technological advances is making control system designed around a prime reliable digital electronic computer which meets the control requirements for the advanced engines and eliminates the need for a hydromechanical control. Electronic propulsion control are currently being applied in several of the latest military aircraft.

A design of an intake control, considering changes through the engine as flight speed, altitude and climatic conditions, is reported synthetically in Appendix.

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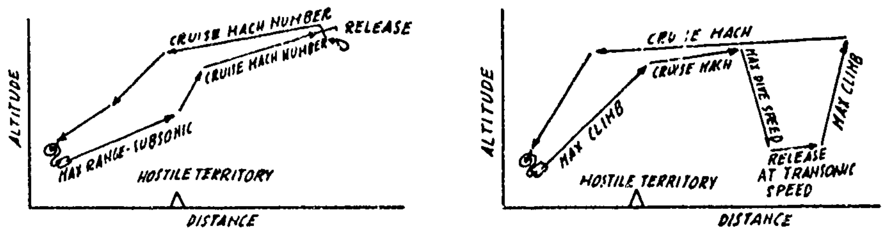


Fig. 1 - Mission profile for the ground attack aircraft.

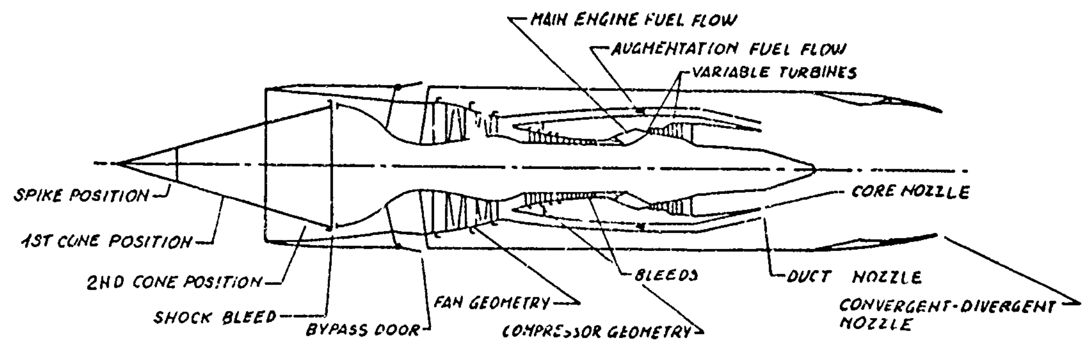


Fig. 2 - Variable geometry two-shaft by-pass ratio powerplant.

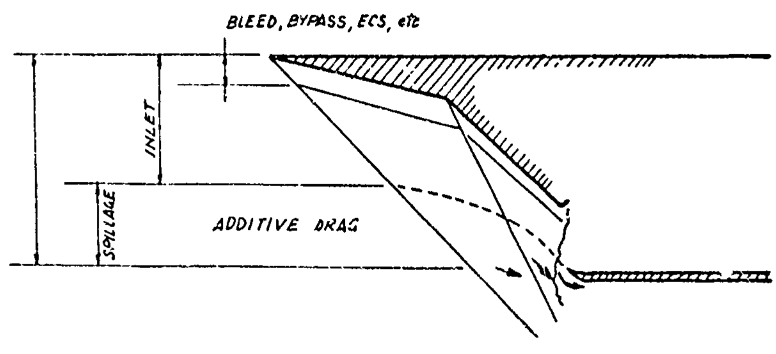
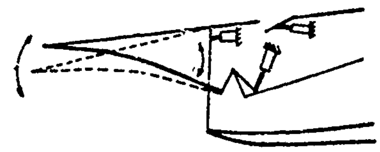


Fig. 3 - Inlet spillage flow (schematic).



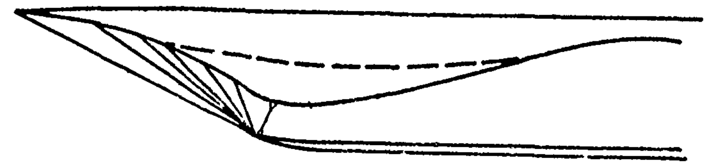
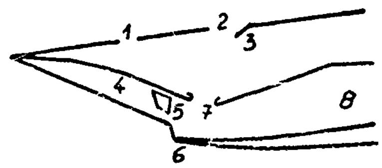


Fig. 5 - External compression inlet.



1. RAMP BLEED EXIT
2. SLOT BLEED EXIT
3. BYPASS DOOR
4. POROUS BLEEDS
5. SIDEPLATE BLEED
6. BLUNT LIP (12° INCLINATION)
7. SLOT FLOW BLEED/BY-PASS
8. DIFFUSER

Fig. 4 - F-15 inlet control system.

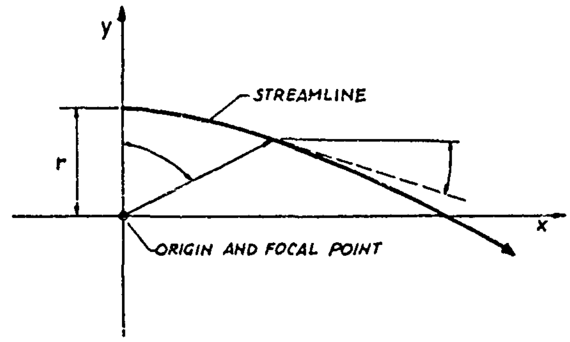
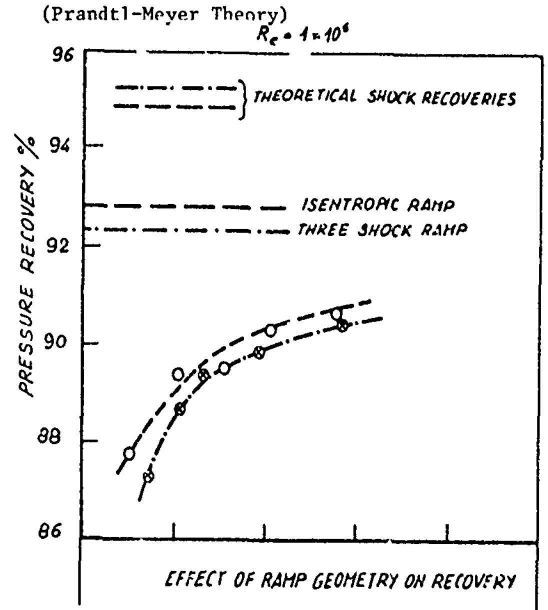


Fig. 6 - Two-dimensional isentropic flow
(Prandtl-Meyer Theory)

Fig. 7 → →

Effect of ramp geometry on recovery.



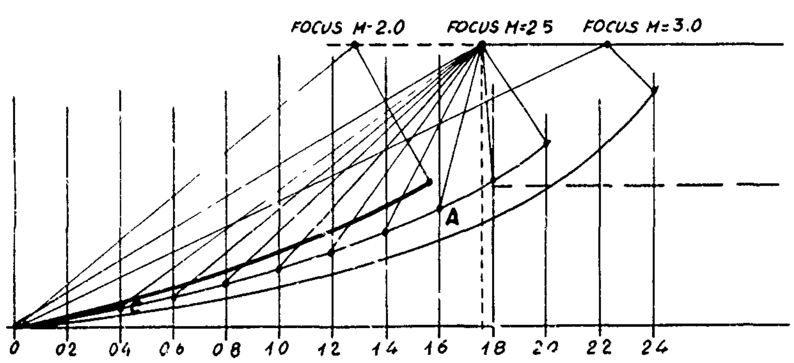


Fig. 8 - Contours and focuses of isentropic ramps.

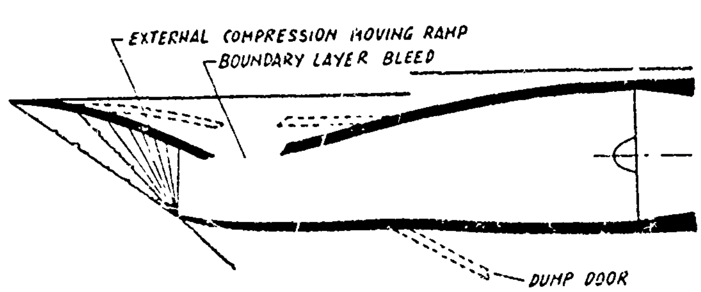


Fig. 9 - External compression two-dimensional inlet.

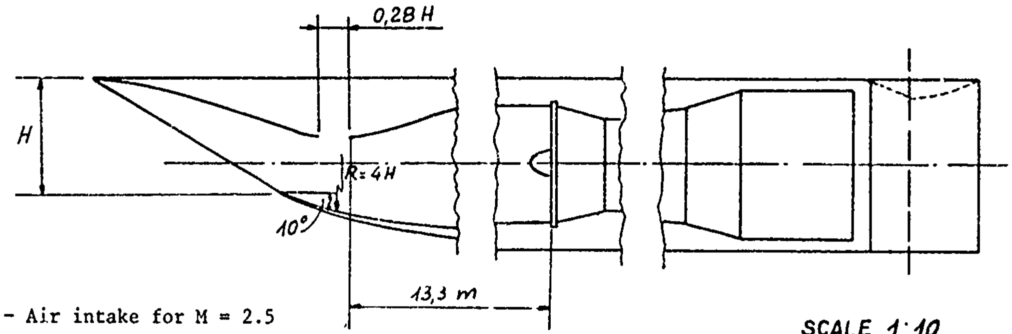


Fig. 10 - Air intake for M = 2.5 and 70 000 N dry thrust engine

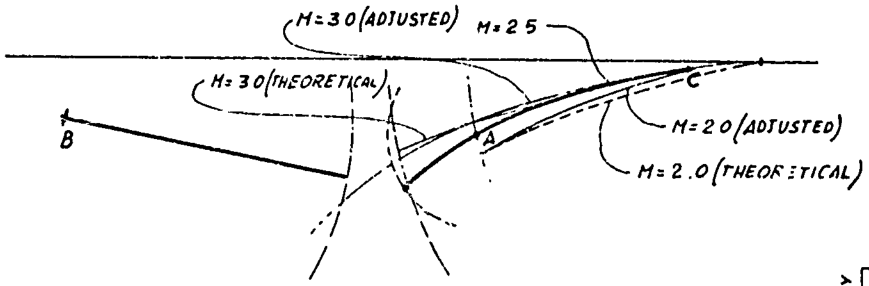


Fig. 11 - Flight speed adjustment by rotation of the first ramp.

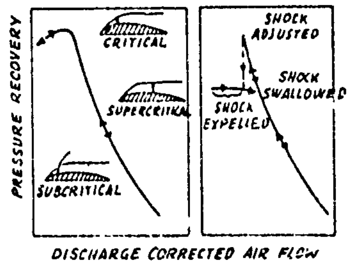
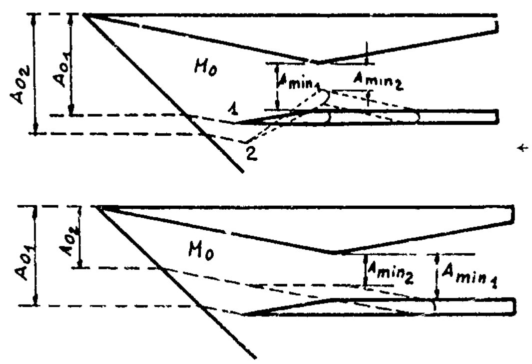


Fig. 12 → →

Comparison of inlet characteristics: external compression (left); internal compression (right).



← ← Fig. 13

Pressure recovery by variable intake.

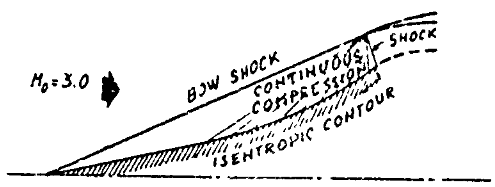
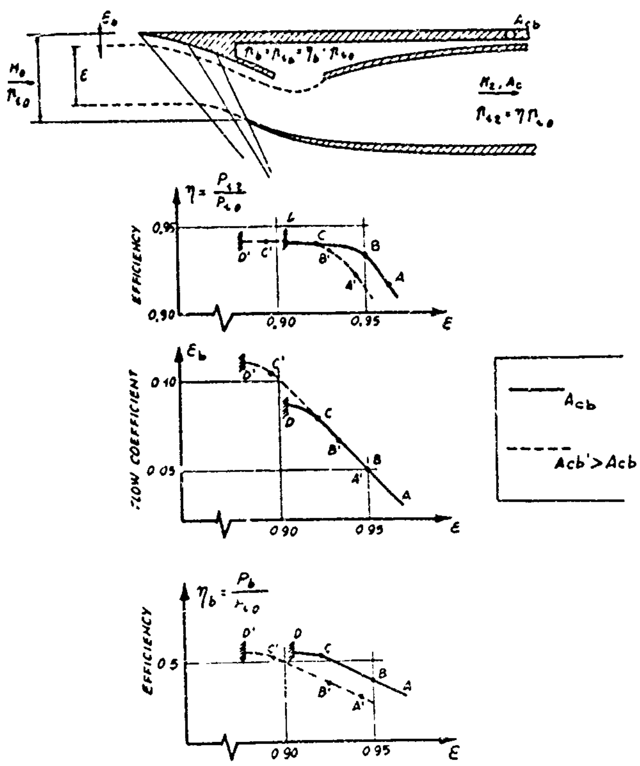
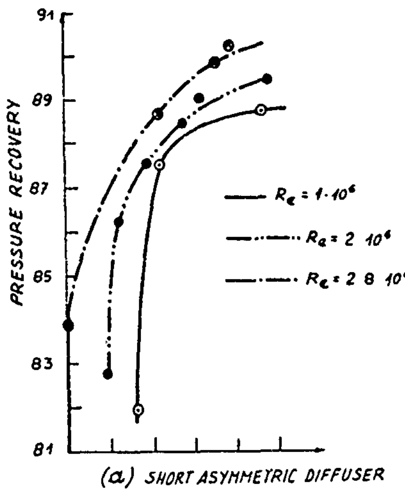


Fig. 14 - Isentropic compression profile for M_o = 3.0.



← ← Fig. 15 - Two-dimensional inlet performances.



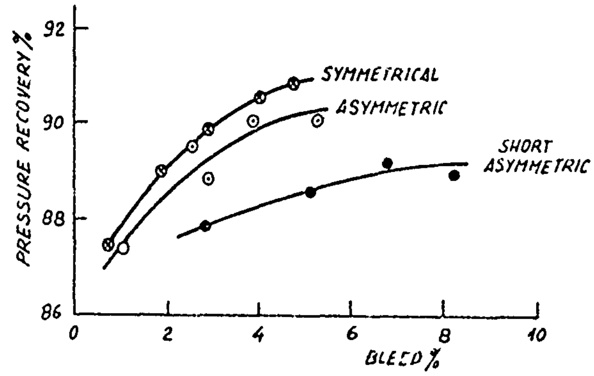
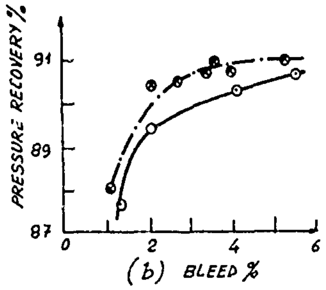


Fig. 16 - Aerodynamic profiles. Combined external/internal compression intakes.



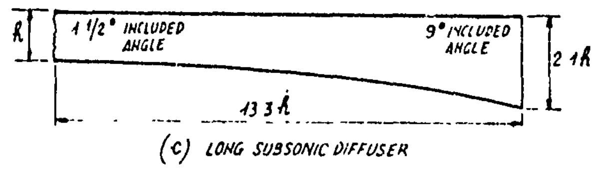
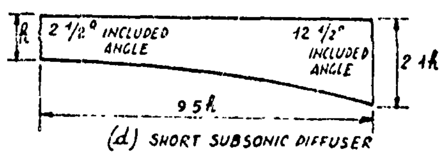
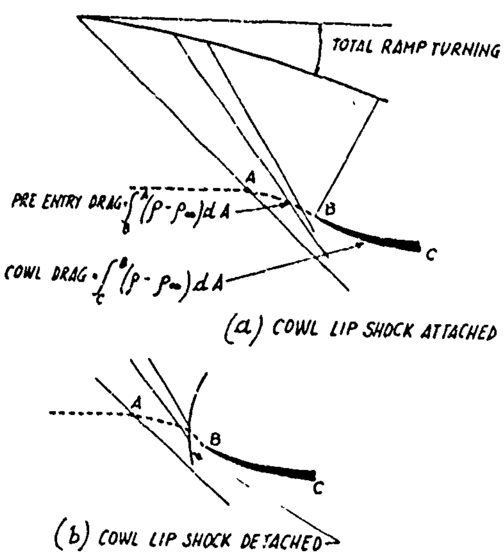


Fig. 17 → →

Subsonic diffuser configurations.





← ← Fig. 18 - Cowl lip configurations.

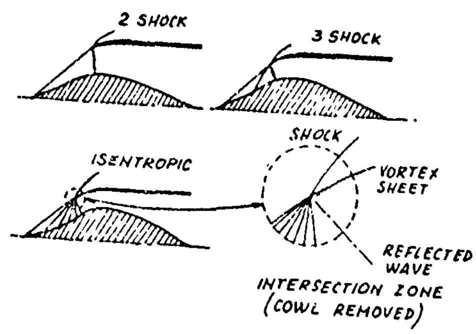


Fig. 19 - External compression inlet.

Fig. 20 - Maximum pressure recovery (all external compression).
↓

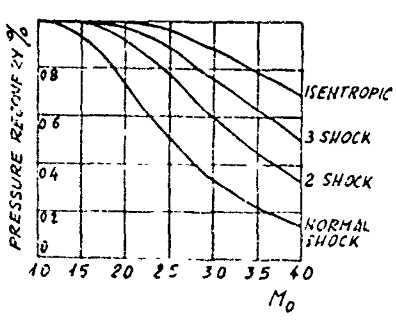
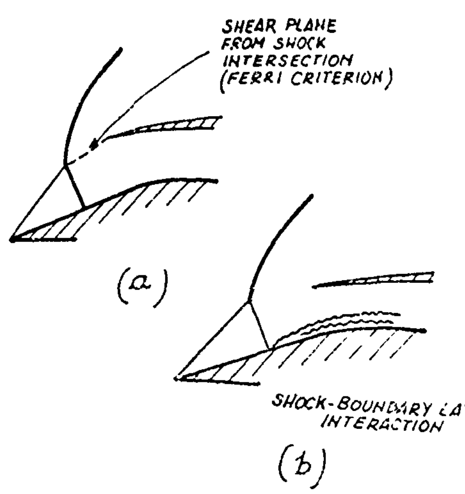


Fig. 21 - 22 → →

Origins of intake instability.



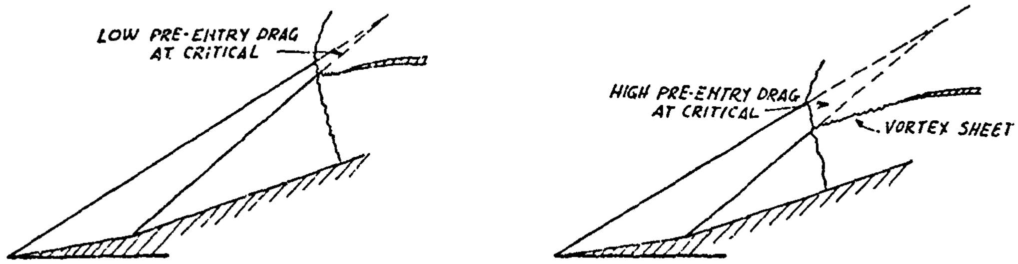


Fig. 23 - Relationship between Ferri type instability and pre-entry drag.

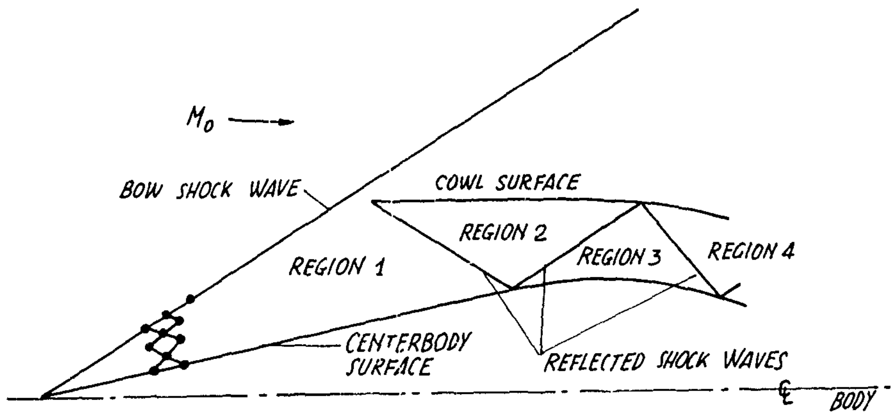


Fig. 24 - Flow field for bow shock not intersecting the cowl.

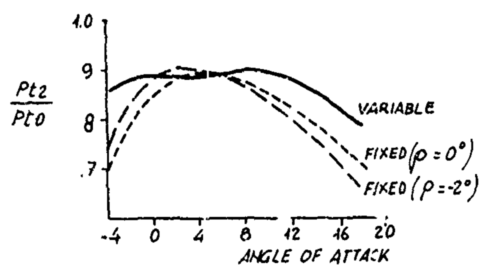


Fig. 25 - F-15, fixed verus variable capture recovery (M = 2.2).

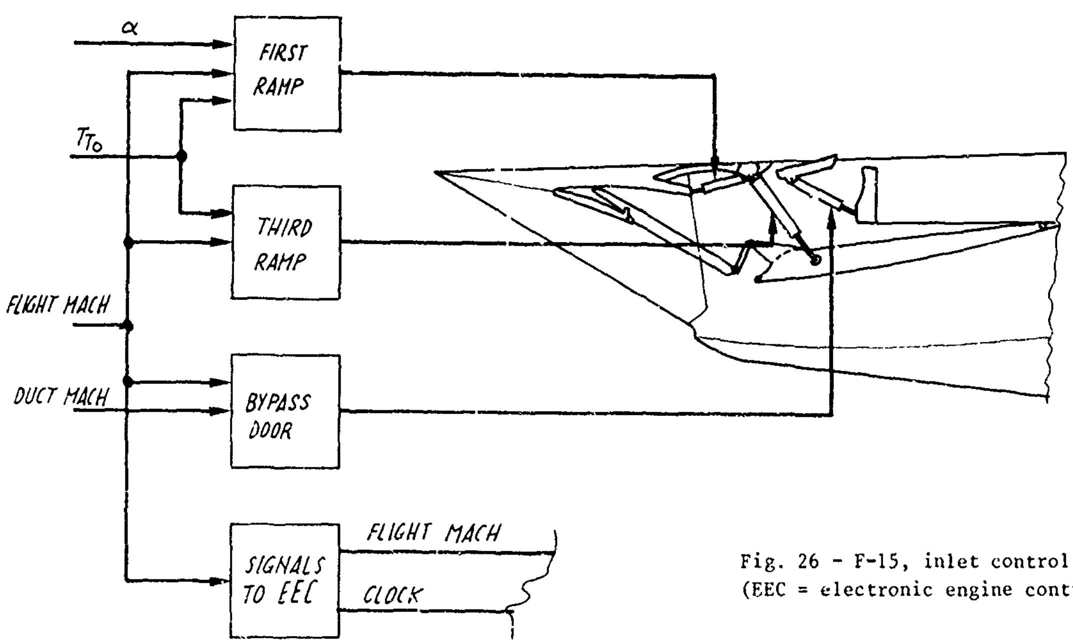


Fig. 26 - F-15, inlet control (EEC = electronic engine control).

DETERMINATION DE LOIS OPTIMALES DE MONTEE EN REGIME D'UN TURBOREACTEUR

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Résumé:

On peut distinguer deux modes de fonctionnement pour un turbo réacteur simple corps sans post-combustion:
-changement de point de consigne
-régulation d'un point de consigne

Nous cherchons à réaliser un changement de point de consigne rapide mais assurant des marges de sécurité convenables au cours de la transition et laissant en fin de transition le moteur dans un état pratiquement stabilisé.

Les commandes du moteur sont le débit carburant et la section de tuyère. Elles sont délivrées par des actuateurs commandés eux-mêmes par un calculateur numérique ou analogique ou électro-hydromécanique. Nous ne cherchons pas les lois de commande des actuateurs mais directement leur sortie c'est à dire le débit carburant et la section de tuyère optimaux. Les lois trouvées seront les consignes affichées sur les actuateurs.

Notations:

N=régime de la turbine
T5=température devant la turbine
M=marge de pompage du compresseur
F=poussée du moteur
C=débit carburant
S=section de tuyère

A(N,C,S)=d(N)/dt = dynamique de la turbine

I. - FORMULATION MATHEMATIQUE DU PROBLEME

Nous supposons l'existence d'un modèle mathématique du moteur et nous adoptons une formulation où le souci de sécurité apparaît comme une contrainte, la rapidité de la transition comme une performance à optimiser.

I-1 Modèle mathématique du moteur

Nous supposons connu un ensemble d'équations permettant d'obtenir à l'issue de calculs plus ou moins complexes les valeurs de (A,T5,M,F) quand on connait (N,C,S) et les conditions de vol.

Il est important de remarquer que si la complexité du modèle est indifférente, la méthode présentée n'est applicable que s'il n'y a qu'une seule équation différentielle (ordinaire). On ne pourra donc pas traiter le cas des moteurs double corps ni prendre en compte certains effets pneumatiques ou thermiques.

I-2 Contraintes

Elles traduisent les marges de sécurité à observer:

$N \leqslant N_{max}$	régime maximal
$T5(N,C,S) \leqslant T5_{max}(N)$	température maximale
$M(N,C,S) \geqslant M_{min}$	marge de pompage
$\left.\begin{array}{l} S \geqslant S_{min} \\ S \leqslant S_{max} \end{array}\right\}$	butées de tuyère

Les 4 dernières contraintes définissent pour N donné un domaine admissible $\mathcal{U}(N)$ de (C,S).

I-3 Critères d'optimisation.

Il est légitime de songer en premier lieu à des critères de temps minimum par exemple : obtention de 95% du régime affiché (ou de la poussée correspondante) en temps minimum.

Avec ce type de critère on obtient en fin de transition des accélérations de turbine importantes et l'on observe aussitôt après un dépassement de régime.

Nous préférons définir un critère tel que le moteur soit pratiquement stabilisé en fin de transition. Pour cela on peut fixer à priori la durée T de l'évolution, assez grande pour que le régime stabilisé puisse être atteint, et en imposant de plus que le régime ne dépasse jamais la consigne N^*.

Sur l'horizon (0,T) on optimisera le critère:

$$I = \int_0^T F \, dt$$

Ce critère est raisonnable quand on envisage une montée en régime. Il est discutable pour une réduction de régime. Nous verrons plus loin que la méthode proposée est applicable avec tout critère de type intégrale. Il est donc possible de changer de critère si l'on veut optimiser une réduction de régime.

I-4 Synthèse de la formulation pour une montée en régime

Etant donné le système décrit par:

$d(N)/dt = A(N,C,S)$	équation d'état	
$F(N,C,S)$	poussée	sorties du système
$T5(N,C,S)$	température devant turbine	
$M(N,C,S)$	index de stabilité du moteur	
C	débit carburant	variables de commande
S	section de tuyère	

maximiser le critère $I=\int_0^T F(N,C,S)\,dt$ où T est fixé à priori ,

en respectant les contraintes:

$$N \leqslant N^* < N_{max}$$

$$\left.\begin{array}{l} T5(N,C,S) \leqslant T5_{max} \\ M(N,C,S) \geqslant M_{min} \\ S_{min} \leqslant S \leqslant S_{max} \end{array}\right\} \longrightarrow \text{pour } N \text{ donné } (C,S) \text{ appartient à } \mathcal{U}(N)$$

II. - RESOLUTION DU PROBLEME

II-1 Utilisation du principe du maximum

Nous appliquons le principe du maximum de Pontrjagin.

Il consiste à exprimer qu'à l'instant t sur (0,T) , il existe un coefficient ψ (système adjoint) tel que les commandes optimales $(\hat{C},\hat{S})$ à cet instant maximisent , sous réserve des différentes contraintes le Hamiltonien :

$$H(C,S\ ;\ N,\psi) = F(N,C,S) + \psi\, A(N,C,S)$$

Ce Hamiltonien doit être considéré comme une fonction de (C,S) où N et ψ sont des paramètres connus à l'instant t.

Le principe du maximum apparaît comme la recherche d'un compromis entre la maximisation immédiate de la poussée F et le choix d'une variation de N (choix de A) qui permettra aux instants suivants d'obtenir une poussée intéressante.

On démontre que ψ obéit à une équation différentielle où figurent les dérivées par rapport à N de F , A et des contraintes T5 et M .

Cette équation permet de démontrer que le maximum du Hamiltonien est constant dans le temps à condition que le problème soit stationnaire , c'est à dire que la solution ne dépende pas du choix de l'instant 0.C'est évidemment le cas dans notre problème.

On peut résumer les résultats théoriques essentiels par:

$$(\hat{C},\hat{S}) \text{ maximise } H(C,S\ ;\ N,\psi) \text{ avec } (\hat{C},\hat{S}) \in \mathcal{U}(N)$$

$$H(\hat{C},\hat{S}\ ;N,\psi) = \text{constante}$$

II-2 Résolution graphique

Le Hamiltonien peut s'interpréter comme le produit scalaire des vecteurs:

$$OX=\begin{pmatrix}1\\ \psi\end{pmatrix} \quad OY=\begin{pmatrix}F\\ A\end{pmatrix}$$

Portons ces deux vecteurs dans un plan.Au domaine admissible $\mathcal{U}(N)$ de (C,S) on peut associer le domaine $\mathcal{Y}(N)$ de Y .Connaissant (C,S) on en déduit Y et réciproquement. (cf. figure 1)

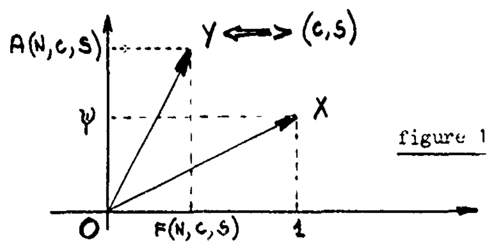

figure 1

Comme $(\hat{C},\hat{S})$ maximise le produit scalaire $OX.O\hat{Y}$ le point $\hat{Y}$ associé à $(\hat{C},\hat{S})$ est le point du domaine $\mathcal{Y}(N)$ qui a la plus grande projection sur le vecteur OX. (cf. figure 2)

On sait donc trouver géométriquement $(\hat{C},\hat{S})$ connaissant (N,ψ).

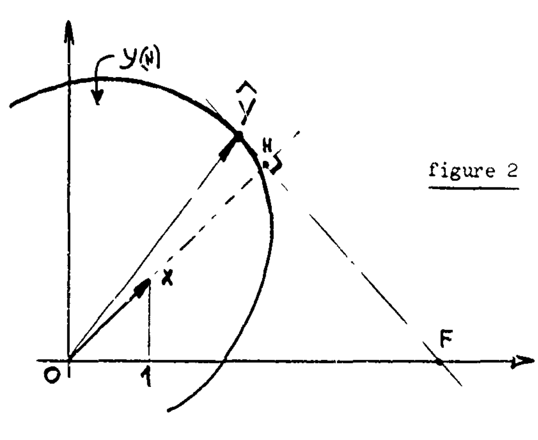

figure 2

Le pied de la perpendiculaire issue de $\hat{Y}$ sur OX est H et $\hat{Y}H$ coupe l'axe des abscisses en F.

En jouant sur les propriétés du produit scalaire on trouve successivement que.

$$H(\hat{C},\hat{S}\ ;\ N,\psi)=OX.O\hat{Y} = OX.OH = OX.OF = O1.OF$$

L'abscisse de F est égale au maximum du Hamiltonien.C'est donc une constante et le point F est donc fixe au cours de la transition.

si on connait F on calcule $(\hat{C},\hat{S})$ en menant de F une tangente au domaine $\mathcal{Y}(N)$.

A priori il existe au moins deux tangentes.Pour notre application le domaine $\gamma(N)$ a toujours été convexe:Deux tangentes seulement sont possibles.Des développements théoriques montrent que pour une montée en régime il faut choisir celle qui donne dN/dt positif.Le bon sens le laissait pressentir.

Le problème est donc de trouver le point F.

Si on postule que le régime de consigne N^* est atteint et stabilisé en fin de transition alors:

$$H(\hat{C},\hat{S}\ ;\ N^*,\psi)=F(N^*,C,S)+\psi A(N^*,C,S)$$

$$\text{avec } A(N^*,C,S)=0$$

Le maximum du Hamiltonien , c'est à dire l'abscisse de F , est égal à la poussée stabilisée maximum du régime de consigne.Des conditions théoriques d'optimalité dites "conditions de transversalité" confirment le postulat sous réserve que le domaine $\gamma(N)$ soit convexe et que le maximum de poussée stabilisée soit une fonction croissante du régime.

III. - METHODE PRATIQUE DE CONSTRUCTION DES LOIS DE COMMANDE

Pour plusieurs valeurs de N : $N_1, N_2, \ldots, N_{max}$ on exploite le modèle mathématique donnant A,F,T5 et M afin de construire les frontières des domaines $\gamma(N_1)$, $\gamma(N_2)$, ... , $\gamma(N_{max})$ que l'on gradue en C et S. Ce calcul se fait en explorant par exemple les valeurs possibles de C pour S fixé et en surveillant les valeurs des contraintes.

On reporte ces frontières sur un même système d'axes rectangulaires (cf. figure 3)

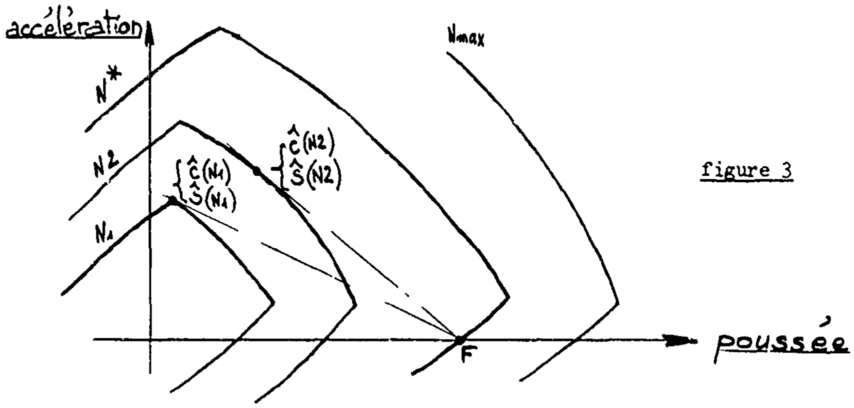

figure 3

Pour calculer les lois de montée au régime N^* on fixe le point F comme étant le point de poussée maximale au régime stabilisé N^*.On mêne ensuite les tangentes issues de F aux frontières des domaines $\gamma(N)$ et on sélectionne celles qui donnent un point de tangence où $A \geq 0$.

On lit les graduations et on construit ainsi les lois de commande en boucle fermée $\hat{C}(N)$ et $\hat{S}(N)$.

IV. - AUTRES APPLICATIONS DE LA METHODE

La méthode proposée ne fait aucune hypothèse sur les fonctions A,F,T5,M.Elle est applicable à tout problème se posant de la façon suivante:

- -problème stationnaire
- -une seule équation différentielle
- -horizon d'optimisation fixé à priori
- -critère de type intégral
- -diverses contraintes de type instantané

V. - CONCLUSION

Le principe du maximum de Pontrjagin nous a permis de calculer des lois de commande en boucle fermée pour un réacteur simple corps.Cette méthode , simple de mise en oeuvre , peut être intéressante au niveau du bureau d'études notamment pour évaluer à partir d'un modèle mathématique les performances dynamiques que l'on peut attendre d'un moteur en projet.

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DISCUSSION

B.J.Cocking, UK

Could you please explain how changes on surge margin due to effects such as inlet distortion, affect your work.

Author's Reply

At the time when we carried out this study, we had no suitable compressor model available. Therefore, we were unable to investigate this aspect.

However, the following can be said

This method provides control laws which permit a specific minimum surge limit to be adhered to during build-up of speed, provided that no inlet distortion occurs.

If an inlet distortion is present, this must either be determined and the control laws amended accordingly, or the distortion is ignored, in which case a sufficient surge margin must be provided in order to be able to "catch" the inlet distortion even in the most unfavourable case (which admittedly will penalize effect on the performance under normal operation).

In the case where the inlet distortion can be measured, one has two possibilities of action:

- The control law parameters must in all cases be set in accordance with the flight conditions (inlet temperature and pressure). The parameters can also be determined in accordance with an inlet distortion index. The inlet distortion measurement is just as much a computer input as the speed N and flight conditions P_0 and T_0.
- Control laws determined for operation without inlet distortion can be corrected by control laws for transient conditions, which then act as "trim". These control laws can only be determined by the proposed method.

R.D.Matulka, US

Have you considered mass flow as a state variable?

Author's Reply

No, namely for the following reasons:

- If a state variable is added, the method is inapplicable, as the geometric solution to the problem no longer gives the point of solution, but a series of points which includes the point of solution.
- The dynamics of this state variable are appreciably quicker than those of the turbine and the actuators would not be in a position of being able to issue commands which would take these dynamics into account. It is better to consider the flow as being permanently stabilised, and this is accomplished by resolving specific implicit equations in the engine model.

This approximation appears to us reasonable in as far as the determined control laws do not contain any very rapid change in the fuel flow or nozzle cross-section.

MODE CONTROL
A FLEXIBLE CONTROL CONCEPT FOR MILITARY AIRCRAFT ENGINES

by

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SUMMARY

It can be shown that the control laws of military engines with their extremely varying flight and operational conditions have usually to be tailored around the most critical conditions in order not to cause damage to the engine and also not to endanger the mission flown. It follows that under the majority of operational conditions the engine is controlled with unnecessarily large safety margins. This in turn means that it carries around either too many compressor stages or operates in regions of the characteristics which are not optimal in terms of fuel consumption.

Mode control offers a concept where these extreme conditions are registered and signalled to an electronic control system. This control system then trims and overrides the normal control laws in order to provide the necessary margins required for safe operation so long as the extreme condition prevails.

INTRODUCTION

Control systems of aero gas turbine engines have always had a certain influence on the overall economics of the propulsion system. With modern military engines equipped with an afterburner and a number of variables such as compressor stators and air bleeds this potential has further increased. This potential is a function of the number of engine trims available on a particular engine and the spectrum of different performance and handling requirements for this engine.

Studies have shown that such a sound potential is available for instance in the case of most modern engines for military fighter aircraft. For an engine of this type the principle of Mode Control is explained in a qualitative way. The main objective of Mode Control can be described as "using the correct trim at the right time and only at the right time" in order to avoid costly compromises. In order to achieve this goal two requirements must be met

- clear indication at any instance in time of what is required from the engine
- availability of engine trims in order to cope with the requirements.

TYPICAL OPERATIONAL PERFORMANCE AND HANDLING REQUIREMENTS FOR A MODERN FIGHTER AIRCRAFT ENGINE

An ideal situation would of course prevail if only one type of aircraft could fulfil all possible fighter missions, i.e. a true multirol combat aircraft could be defined and built. Experience has shown that this is not practical because of fairly large compromises that would have to be accepted, making such an aircraft inferior to other aircraft specially tailored around a certain role or mission. However, it is possible to combine a limited number of different missions in the design of a single aircraft. For such an aircraft typical requirements on the propulsion unit could then be as follows:

- Short power transient times near SLS if short take-off and landing distances (thrust reverser) are required
- Maximum possible take-off thrust in reheat
- Low fuel consumption during typical cruise and loiter missions at different altitudes, Mach-Numbers and power settings

- Maximum possible thrust for aircraft accelerations, tight turns and combat
- Short power transients and safe and reliable engine response during dog fights
- High power offtake from one engine particularly in a failure case.

These operational requirements can be translated into the following engine requirements

- sufficient fan and compressor surge margins to cope with fast power transients in both accelerating and decelerating directions
- sufficient fan and compressor surge margins to cope with intake flow distortion due to aircraft incidence or firing of weapons
- sufficient compressor surge margins to cope with shaft power offtake
- maximum dry thrust
- maximum afterburner thrust
- minimum dry specific fuel consumption at cruise ratings.

It can be shown that these requirements usually only exist one at a time, i.e. while for instance maximum dry thrust is required there is no need to make provision for best cruise specific fuel consumption or for good engine handling potential and vice versa.

ENGINE TRIMS TO COPE WITH REQUIREMENTS

Fig.1 shows an example of a military engine with its control variables. The number of control variables also depends on the design philosophy of the engine and the components respectively particularly with items like variable compressor stator blades. For this investigation only those variables have been included which are necessary for troublefree operation of the components within the engine. Not included are the so called variable cycle engines which make use of additional variable geometry in order to actively adjust the thermodynamic cycle to certain missions. Should this type of engine ever be introduced it would lend itself even more to the benefits of Mode Control. However, for this paper the example of a military three-spool by-pass engine equipped with an afterburner has been chosen. Its control variables, shown on the lower half of fig.1, are as follows:

- Intermediate compressor air bleed
- High pressure compressor air bleed
- Engine fuel flow
- Afterburner fuel flow
- Variable nozzle area.

The control of the engine is such that the air bleeds are closed over the important part of the flight envelope when running steady state. In the afterburner off-mode the nozzle area is constant. With the afterburner operational the resulting fan running line is slightly higher than for dry operation.

In fig.2 the optimal running lines for maximum afterburner thrust, dry thrust and lowest cruise specific fuel consumption are shown as an example in a simplified form. The effect of intake pressure distortion is indicated. Figs.3 and 4 show the effects of flow distortion, shaft power offtake and transients together with the effects of compressor air bleeds.

MODE CONTROL - A CONCEPT TO SELECT THE RELEVANT ENGINE TRIM ONLY WHEN REQUIRED

The simple sketches in figs.2 to 4 highlight already one important fact:
Any measures to improve the engine handling limits, such as the use of air bleeds cannot be continuously used over important parts of the flight envelope because of their detrimental effects on steady state performance (thrusts and SFC's). Therefore with the present control system philosophy the datum core compressor running lines without bleed have to be positioned low enough to ensure surge free operation under the most severe combinations of aircraft incidence, power offtake and engine transients. This compromise can entail a fairly heavy penalty on steady state performance in terms of thrust and SFC.

When looking at the time distribution of the various operational requirements the following becomes obvious

operational requirement	approx time prevailing
handling and high power offtakes	seconds
maximum thrusts	minutes
lowest SFC's	hours

It can therefore be concluded that the normal engine matching with its penalties on steady state performance has to be chosen such that no operational problems are to be expected when severe handling requirements prevail just for a few seconds. Mode Control can help to either eliminate, or at least minimize, these performance penalties by matching the engine closer to the optimum steady state performance. This usually means compressor running lines closer to the respective surge lines and use of available engine trims to cope with the special short duration handling requirements.

Fig.5 shows a simple block diagram of the general philosophy of Mode Control. The principle is as follows:

Two sources of information are available in order to determine the actual requirement on the engine at any given point in time, i.e.

(a) aircraft computer, whose data is used to compute flight condition and type and magnitude of flow distortion

(b) pilot's throttle from which adequate information can be derived for determination of what the pilot expects from the engine at any moment of time. Fig.6 interpretes the information to be deduced from the throttle signal.

Not shown in fig.5 is a power offtake signal which in certain cases of relatively high offtake requirements could be useful. A fairly simple, not necessarily very accurate, torquemeter on the drive shaft would be sufficient. The information from the two (or three) sources is then processed in a small computer programme employing a matrix approach. It determines the trim(s) to be selected in order to cope with the prevailing situation in an optimal way.

In order to implement Mode Control successfully it is important to make sure that the response rates of the engine variables or trims are compatible with the requirements, i.e. the respective rates at which a certain problem can develop.

It should be pointed out that because of the type of computing required a digital control system is more suitable for this task than an analogue one.

DEMONSTRATION PROGRAMME

In 1978 a demonstrator programme sponsored by the German government was launched. This programme includes the construction of two flightworthy digital engine controls by 1980. Following checking out on a simulator and an engine in a high altitude test facility it is planned to flight test the complete control system, including Mode Control in an aircraft.

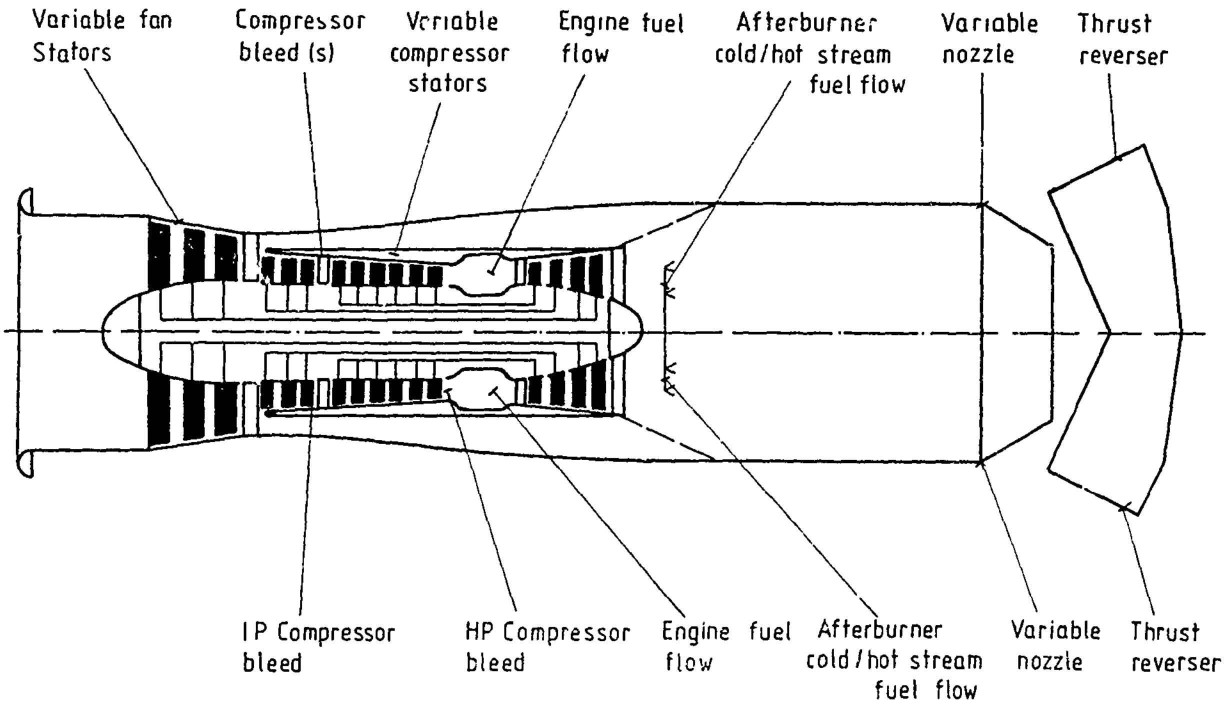

Fig.1 Control variables of a modern military fighter engine in general terms (upper half) and as used for discussion (lower half of sketch)

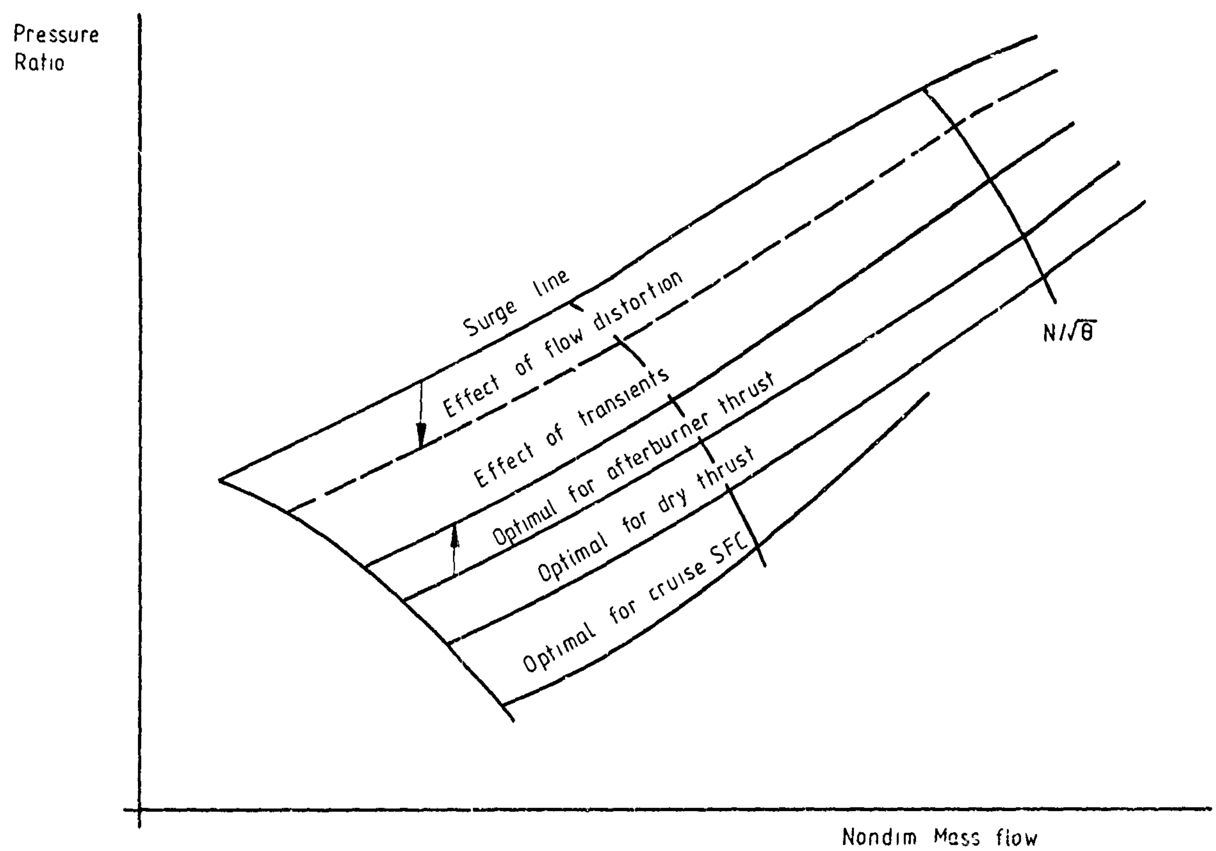

Fig.2 Fan characteristic with different optimal running lines

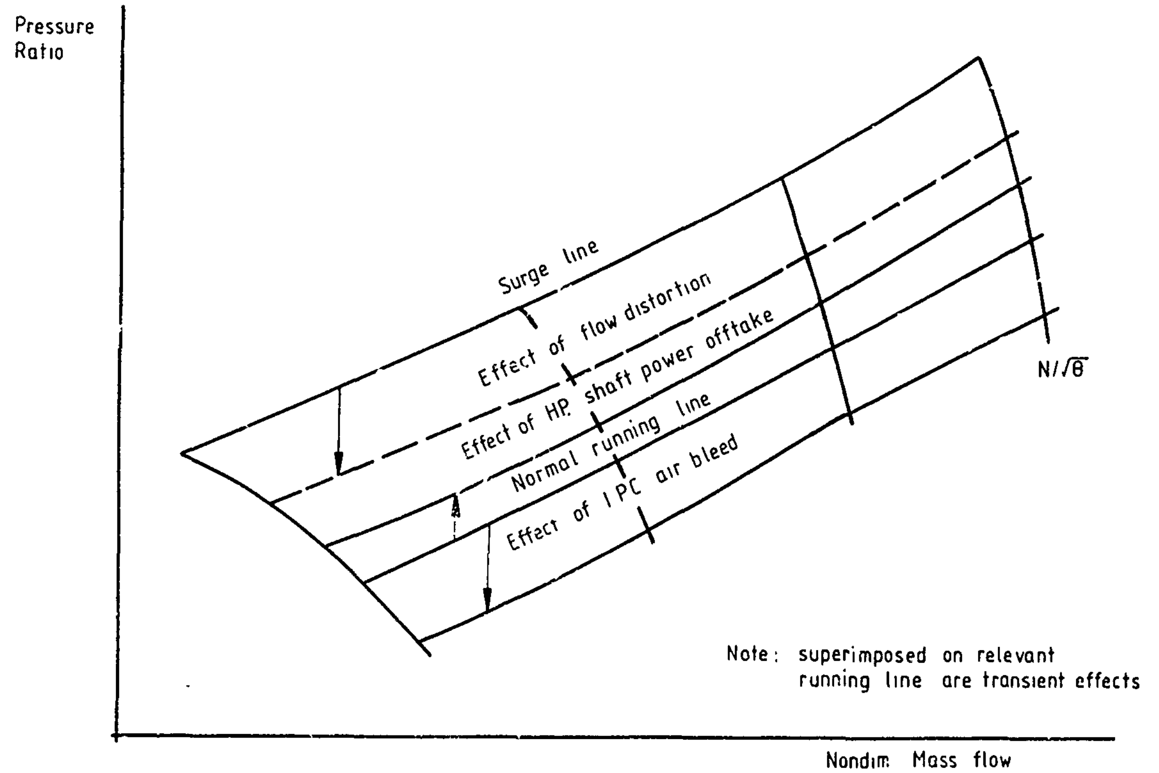

Fig.3 Intermediate pressure compressor (IPC) with operational effects on surge- and running lines

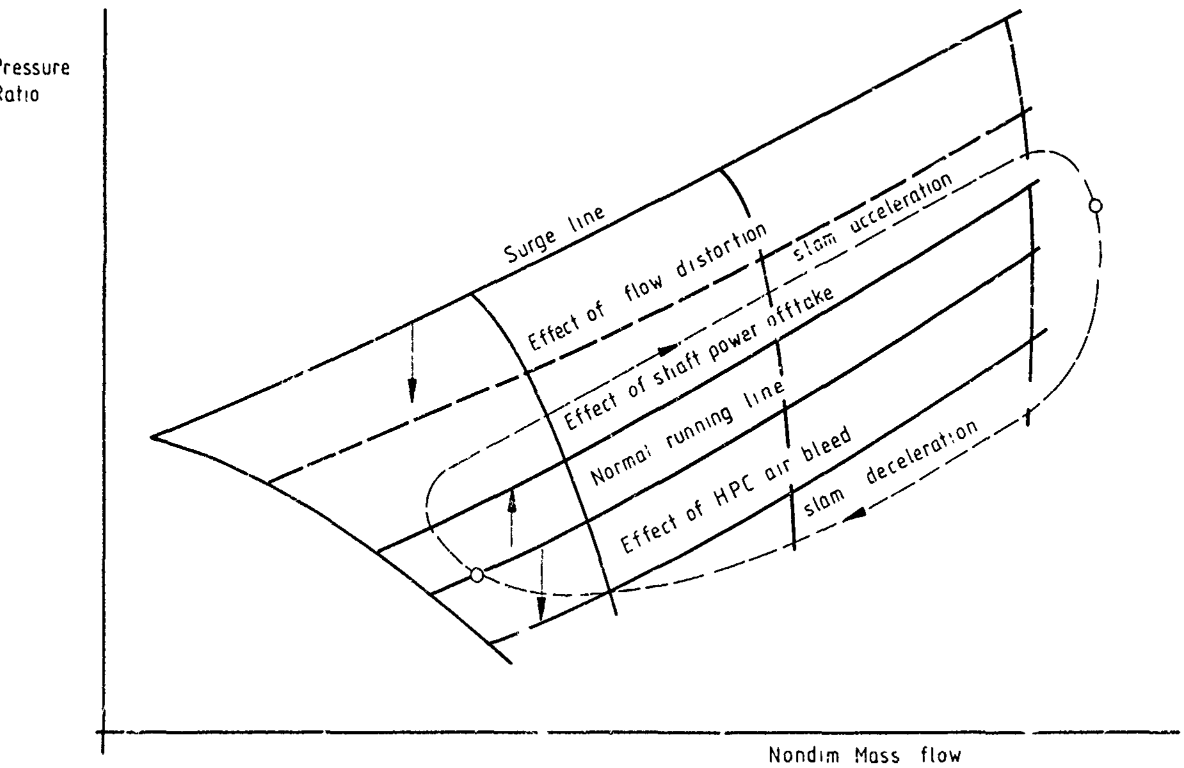

Fig.4 High pressure compressor (HPC) with operational effects on surge- and running lines

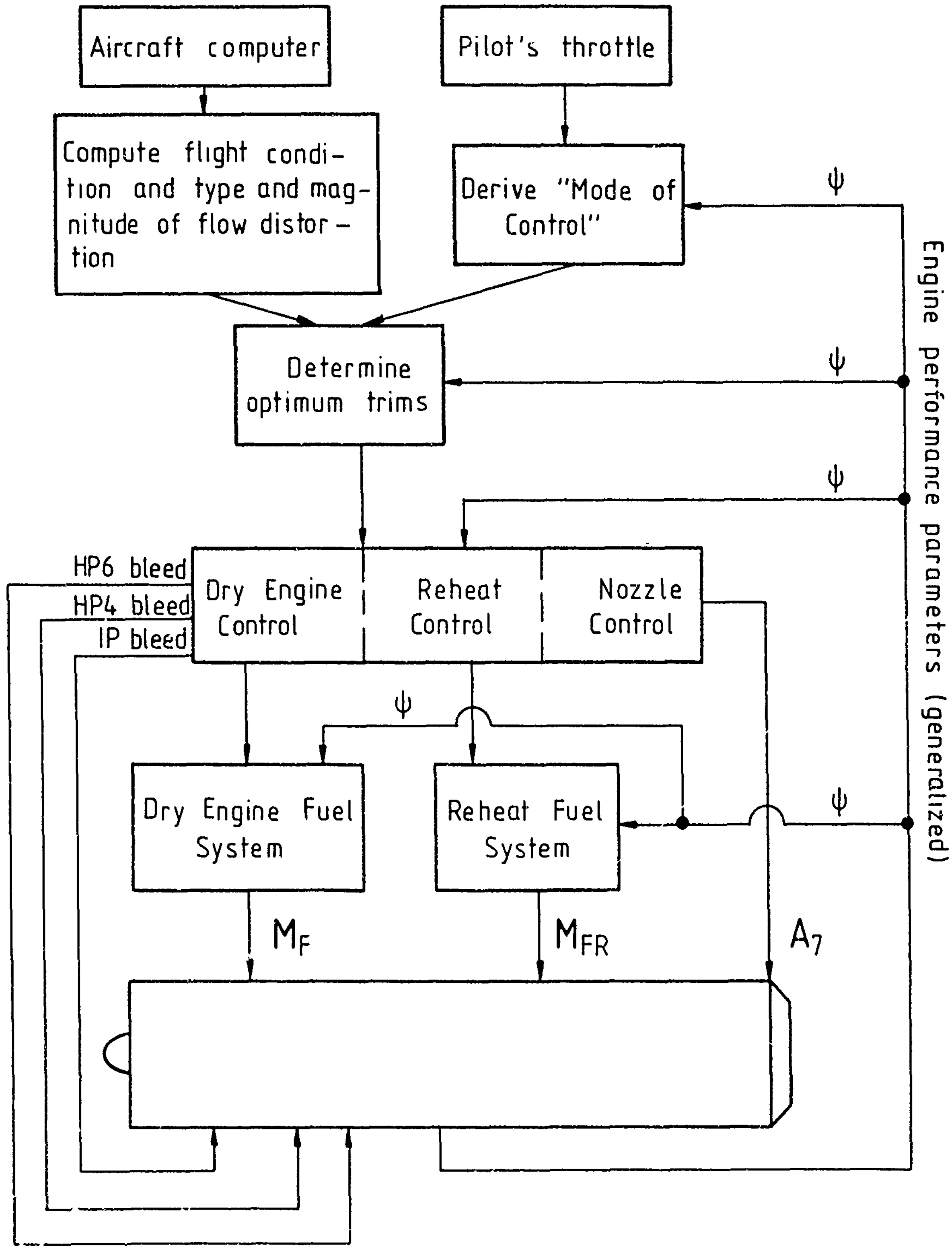

Fig.5 Flow chart of Mode Control

Nº	Mode of Operation	Source of Signal for Selection of the Mode	Essential Requirements
1	Idle	$\alpha = \alpha_{idle}$	lowest thrust
2	Cruise	$\alpha_{max\ dry} > \alpha > \alpha_{idle}$	lowest installed SFC
3	Max Dry	$\alpha = \alpha_{max\ dry}$	highest max dry thrust
4	Max Reheat	$\alpha = \alpha_{max\ RH}$	highest max RH thrust
5	Dry Acceleration	$\alpha_{idle} < \alpha < \alpha_{max\ dry}$ and ($\dot{\alpha} > a$ or $dN_H/dt > b$)	sufficient surge margins
6	Dry Deceleration	$\alpha_{idle} < \alpha < \alpha_{max\ dry}$ and ($\dot{\alpha} < a$ or $dN_H/dt < c$)	sufficient surge margins
7	Reheat Acceleration	$\alpha_{min\ RH} < \alpha < \alpha_{max\ RH}$ and ($\dot{\alpha} > a$ or $dA_7/dt > d$)	sufficient surge margins correct fuelling
8	Reheat Deceleration	$\alpha_{min\ RH} < \alpha < \alpha_{max\ RH}$ and ($\dot{\alpha} < a$ or $dA_7/dt < e$)	sufficient surge margins correct fuelling
9	Slam from Dry into Reheat	$\alpha > \alpha_{min\ RH}$ and ($A_{7max\ dry} < A_7 < A_{7min\ RH}$ or $dA_7/dt > d$)	sufficient surge margins correct fuelling

Fig.6 Identification criteria for mode of operation and requirements on engine

DISCUSSION

R.Smyth, Ge

Idle Thrust Comments to question of speaker concerning idle thrust requirements of civil aircraft.

The present generation of high bypass ratio engines also demands lowest possible idle thrust for comfortable taxying and low fuel consumption in taxi operation. However, at the same time acceleration requirements for time from idle to max power have to be met Generally the airframe manufacturer demands also here the lowest possible idle thrust.

Author's Reply

Yes, this is very true. To keep the acceleration time down it is important to fix the idle speed at not too low a level.

D.K.Andrews, UK

Do you envisage that a mode computation and trim control computer will be integrated with each engine control – or will a separate airframe located computer be used to trim all engines?

Author's Reply

I propose to integrate Mode Control into the individual engine control box mainly on the basis that each engine has its own throttle.

R.D.Matulka, US

Have you considered dividing the idle mode into two input functions. (1) minimum thrust and (2) minimum fuel flow?

Author's Reply

This is not included in our present specification of Mode Control. However, if the pilot positions the throttle just a small amount off the idle minimum thrust position, the engine is automatically trimmed to optimum SFC.

G.E.Davies, UK

I am surprised you have response problems with bleed valves. Is this because you are using switched type bleed valves which select full bleed flow in a single operation? If you had modulating bleed valves you would be able to select the optimum level of bleed flow for any particular situation and also probably obtain better response as well.

Author's Reply

Yes, a valve the flow of which can be modulated would be preferable to a two position valve. I also believe that the response problem can be overcome, but it is an area that requires attention.

J.McNamara, UK

System Configuration. Is the thrust demand (PLA) input better organised if taken through the aircraft computer system in order to compute for high 'G'-turns, intake distortion parameters?

Author's Reply

If during 'G'-turns the flow patterns into the two engines should be substantially different, yes, additional information from the a/c computer may be required.

M.Perks, UK

Thrust Response What background work has been done to confirm that any transient loss of thrust following mode switching during an acceleration is acceptable in terms of aircraft handling?

Author's Reply

In general there should not be a problem if during a transient lasting a few seconds the thrust is reduced by say 4 to 7% However, in certain special cases the possible implications have to be investigated carefully.

REDUNDANCY CONCEPTS IN FULL AUTHORITY ELECTRONIC ENGINE CONTROL - PARTICULARLY DUAL REDUNDANCY

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SUMMARY

Some form of redundancy is almost always required in full authority electronic engine controls. The paper surveys the available methods, and the reasons for their selection in particular applications, with particular reference to the effects of the electro-hydromechanical interface.

The bulk of the paper is devoted to discussion of various 'dual' redundant arrangements and describes practical experience with some of them - particularly the unexpected difficulties.

The paper considers system safety and the variety of failure survival strategies which can be employed. In general, ease of analysis is accompanied by simple failure survival strategies. More complex strategies may result in higher system availabilities and there is therefore a trade-off to conduct between non-recurring design cost and system availability in service.

Military requirements and microprocessors permit more flexible system architectures than before. The impact of these possibilities is discussed and the direction of future developments is indicated.

INTRODUCTION

All the authors have long been active in the field of engine control. The joint activities of Dowty Fuel Systems and Smiths Industries in digital engine control go back for many years before their formal association as Dowty and Smiths Industries Controls Limited and the work described in this paper is in some sense a history of these joint activities up to the present day.

The objective of the paper is not however, historical but is to present some of the reasons behind current system thinking using past experience by way of illustration.

Technical Requirements

The engine control system designer often finds himself in an unusual position compared with the designers of many other aircraft systems. On the one hand only a relatively small budget in terms of size, weight, power consumption and system cost is available compared with the budget associated with, for example automatic flight control, and yet on the other hand the safety implication of loss of engine power and even more so of secondary airframe damage due to engine power runaway, approach the safety implication of loss of flight control. There is, therefore, a continuous pressure on the engine control system designer to arrive at system compromises between performance and safety.

There were also differences in the evolution of the two types of control. The move from simple "rod and cable" operation of flight control surfaces to automatic flight control was accompanied by a significant level of redundancy in the electro-mechanical systems. Engine control, on the other hand, moved rapidly to the sophisticated simplex (i.e. non-redundant) but highly reliable hydromechanical systems to be found in the majority of present day aircraft.

All such systems rely, for continuity of control, on the high integrity of well designed simplex parts. Many of the systems also rely on these simplex parts in order to avoid overspeed. This extensive reliance on single components is, in part, made possible by the grading of "authority", i.e. the degree to which the fuel flow can be affected by the various parts of the system.

Some engines used redundancy in their overspeed limiters (Figure 1) which, in many U.K. designs, used separate valves for flow control and limiting. Many of the limiters, particularly temperature limiters were electronic. Development of engine technology led to ever increasing demands on the control system both in terms of accuracy and complexity and the designers of the 60's started to include quite complex electronic 'trimming' controls and, building on their existing experience, tended to accept simplex configurations with limited electronic authority over the engine working point.

These analogue electronic trimming controls are used on many current aero-engines e.g. RB.211, TF.41, TF,30, Spey, Pegasus, etc.

Many trimming systems are redundant in the sense that adequate control can be retained after failures in the trimming function. This makes it possible to accept higher failure rates for trimming than could be tolerated for primary control functions. The first digital systems to enter service exploited this feature by applying sophisticated trimming functions to a fairly conventional hydromechanical control system in a control configuration called "Supervisory" (Figure 2).

The arrangement illustrates very well the conflict between economics (or performance) and safety which, as mentioned earlier, is a dominant feature of the design of electronic controls for engines. The benefit of the supervisory system is that it improves performance when it is operating but its failure cannot hazard the aircraft. The other side of the coin is the need to carry a complete hydromechanical system as well as the electronics and the fact that the very authority limitation which makes it safe can also prevent it achieving the full performance benefits which are possible. The full authority systems discussed in this paper seek to resolve the safety issue without imposing limits on performance. At the same time, they allow the hydromechanical content of the system to be reduced and simplified.

While engine controls had been developing the electronic trimmer theme, the flight control designers developed electronic and electro-mechanical redundancy full authority systems for such applications as auto-landing and fly-by-wire. From this flight control experience came a new world of semi-statistical design analysis techniques which were required to build up confidence in the systems prior to actual flight experience. Indeed it soon became obvious that flight experience would never really measure the demanded safety levels directly, the best that could be hoped for being the build up of confidence in some of the assumptions used in the safety analysis. Hence, when the time came to introduce full authority electronic engine controls, the safety and reliability analysis was usually done from the background of this flight control experience, rather than from the background of the traditional hydromechanical engine control.

As illustrated by the supervisory system above, the electronic engine control designer, whether working in the analogue or the digital field was therefore under two pressures. Firstly to continue designing with the basic economy of the traditional hydromechanical control and secondly to meet ever increasing demands of statistically provable safety.

The design team with which the authors have been associated over this period, has been trying to find acceptable compromise solutions to this dual requirement. This search has led at intervals to our being described as pedants, starry eyed idealists and downright specification dodgers!!

<u>The first system design</u>

At the beginning we felt that there would be no real possibility of the industry accepting engine control system designs which relied on more than two complete paths or 'LANES'. The first such solution proposed was for the PS50 engine and consisted of two sets of input transducers, two digital computers and a simplex actuator of the proportional solenoid type for the main engine control and additional permanent magnet stepping motor actuators for the various afterburner fuel flows and nozzle control. (Figure 3).

The two computers exchanged transducer data via optical unidirectional data links and proceeded to use average data for control unless the data from the two LANES was outside a predetermined tolerance. The outputs of the two computers were also exchanged and compared by both. If both agreed that the comparison was good, one of the two lanes drove the actuator controlling the engine. No provision was made for driving the actuator from the other lane, or for determining which of the two lanes was faulty. It followed that if either lane detected a failure, the actuator was disconnected and the overall engine system degraded into (a) hydromechanical back-up control of the main engine (b) frozen reheat flows which could be manually shut down.

This system was successfully operated on a test bed and shown to have all the necessary safety features except the ability to continue operation after most first failures. Failure survival was limited to deleting functions (e.g. temperature limiting) associated with single sensors and which were traditionally "trimming" functions. A second set of equipment was therefore built which was aimed at adding ability to continue operating with full performance after any first failure.

The Improved System Design

If any system is to survive a first failure at an acceptable rate it must satisfy three major requirements:-

(a) 'Single thread' elements must be few and highly reliable.

(b) The reconfiguration mechanism must have a comparable success rate.

(c) The failed element must be reliably excluded from the reconfigured system.

Examination of the first system showed that (a) could be met if the simplex main engine and nozzle control actuators were replaced by dual drive units. In this system as in all DSIC systems isochronous governing was achieved by using the stepping motor as an output integrator. This allows the digital computer to recover rapidly from any power failure causing loss of temporary stored control data, by minimising the time dependence of the system on such data. It was also required that the relationship between actuator position and fuel flow be stable, so that in the event of digital control shut-down, the fuel flow remains constant until recovery action is taken by the back-up system. In the case of afterburner control, a known and accurate relationship between actuator position and fuel flow is also required in order to avoid the need for some form of fuel flowmeter feedback to the electronic controller.

Meeting the last requirement proved to be much easier on paper than expected in a two lane system. Briefly, the system operated with both lanes active when both lanes were failure free. Inputs were exchanged as in the case of the first system and the lanes exchanged output data as before. If both agreed, both motors were driven and the mechanical outputs consolidated by summing in a differential gearbox (Figure 4). If the two lanes disagreed, the idler cage of the differential rotated and operated a mechanical switch which disconnected the two motors, thus freezing the system. Both lanes then entered a self-check process and if one and only one self-tested as faulty the other was allowed to continue control. This process can only result in a wrong reconnection if the good lane self-tests as 'bad' and the bad lane simultaneously self-tests as 'good'. The probability of wrong connection is very low provided that the decision based on the self-tests can be executed with acceptable error. In the system which was tested, the decision mechanism itself was duplicated and dual failure would be necessary to allow the connection of the wrong lane. A flight standard system was fully evaluated on an Adour engine (Figure 5-6). What proved to be far more difficult was to prove, partly by analysis, requirement (b) - that the reconfiguration itself would be successful as often as was specified.

This improved system was built and tested. Full fault recovery tests, including tests in which faults were introduced in the middle of full speed slam accelerations and in the middle of fast reheat aquisitions and throttle movements showed the ability of the system to react correctly to induced faults. Difficulties were experienced however after an unexpected failure of the HP pump followed by intermittent stalling of both halves of the dual motor actuators. This effect, which is discussed later, served to illustrate the importance of ensuring that the external environment of any redundant system is unlikely to cause common mode failures and that late consolidation is desirable.

At no time during the system tests and trials, which covered fifteen hundred hours of rig and engine time, was there any indication that the system organisation required revision in principle.

During these tests use was made of early versions of modular software design procedures which include comparison of test results obtained on two dissimilar processors and coded independently. Improvements were also made to the computer and software organisation and in particular the need for close synchronisation between the two lanes of the system was removed.

Other System Configurations

The supervisory control and the fully duplicated system design represent the two poles of system design. Between them lie a range of full authority systems using limited replication and technology which may be dissimilar.

Pegasus Engine Control

The existing system on the Pegasus engine uses an electronic limiter and also a redundant and much simplified hydromechanical flow control for use after a failure in the main hydromechanical control (Figure 7). Full authority digital control of the Pegasus engine has been demonstrated by Dowty and Smiths Industries Controls Limited, together with two different forms of reversionary control. One form was hydromechanical; the other was electronic. Both provided automatic changeover after a failure in the full authority digital control. The existing system used manual changeover and involves a power excursion which both the newer systems avoid.

The reversionary systems are much simpler than either the existing hydromechanical main control or the full authority digital control. Their prime purpose is to allow the aircraft to be landed safely after a failure in the main control. The automatic changeover allows failure to be survived while the aircraft is hovering - a capability which the existing system does not possess.

The design of the reversionary controls is aimed at meeting the minimum safe handling capability with the least possible hardware. In contrast to the Pegasus, in the exploratory Adour system mentioned earlier, the target was to retain full specification performance after a failure.

Different design trade-offs can be made. The reversionary systems which have been demonstrated on Pegasus are minimum hardware systems. They simply provide safety and a "get-you-home" capability. A second design objective would be some level of enhanced reversionary capability which provides a better match between complexity and performance.

Figures 8 and 9 show the levels of performance achieved during test-bed development. Figure 8 shows transient-free reversion to the emergency hydromechanical system. Figure 9 shows a reversion to the electronic reversionary system during an engine acceleration. The only inputs to the reversionary system were power demand and H.P. spool speed.

Helicopter Engine Control

The electronic arrangement demonstrated for Pegasus applies one or other of the electronic control outputs to the same flow control valve using a single drive motor. The arrangement used for the Adour system combined two motor outputs via a mechanical consolidation to drive a single valve. The authors are also working on a digital full authority system for helicopter engines in which the point of consolidation is in the valve assembly itself.

In other respects the system structure is like that described for Pegasus using electronic reversion. In this application the engine is planned to be used in a twin-engined helicopter with the two power turbines mechanically coupled to a single rotor. The arrangement is one which, after a first failure, allows power modulation to be provided by one or other of the engines while, over large parts of the flight envelope, the other is held on a fixed power setting. The infrequent need for power changes on the second engine make it possible to use a very simple reversionary system and yet, in terms of the vehicle itself, retain unimpaired performance.

The full system arrangement for the aircraft is shown in Figure 10. The hydro-mechanical control section of both the Pegasus and the helicopter control system is greatly simplified compared to a conventional hydromechanical control. Figure 11 shows the valve arrangement for the helicopter control illustrating the method of consolidation of electrical inputs at the valve itself, (see later).

So far we have described four full authority electronic systems. One, the PS50 system, was simply a step in development but it will be clear from the discussion of the other three that there is no single general purpose system design and that the vehicle in which the engine is used plays a major role in influencing the trade-offs and the safety features of any given design.

We have referred earlier to output consolidations and to actuation arrangements in redundant systems. We now turn to these topics in more detail.

Electro-Hydromechanical Interfacing

The electro-hydromechanical interface unit has to provide the means by which the electronic controller influences either the amount of fuel metered to the engine or a variable geometry feature such as inlet guide vanes or exit nozzle area control.

For fuel metering the interface unit generally comprises an electric actuator and a fuel control valve; dual redundancy can be used for both of these sub-units, but it is unusual to justify the use of more than one fuel control valve per discrete function.

There are numerous ways of forming the consolidation of the two electronic control channels. Each of the systems described earlier used a different form of consolidation and each will be discussed in some detail after a few scene - setting observations.

The most simple fuel control interface unit would comprise a motor and a fuel tap. The state of the art has not yet reached this goal because of practical problems in signal transducing and obtaining suitable control loops with acceptable failure modes.

For some simple applications, particularly for dry engines, it is still preferable to retain pressure-sensing bellows, as used in conventional hydromechanical controls, within the interface unit rather than rely on electrical pressure transducers to provide duplicated signals for inclusion in the electronic computations for fuel demand. Thus for a helicopter application an interface unit using an electrical demand of Fe/P_1 (engine fuel flow - total intake pressure) via a hydromechanical sub-unit incorporating a P_1 bellows can be shown to have practical advantages over a unit which meters Fe only,

with the P_1 term being sensed and computed externally to the interface. Similarly for a VTOL application like the Pegasus, there is advantage in using Fe/P_3 (engine fuel flow - compressor delivery pressure). In these units the electric actuator is set by the electronic controller to select a demanded value of Fe/P_1 or Fe/P_3 and this is provided by the hydromechanical elements of the unit.

In the PS50 and Adour engine runs mentioned earlier, we used electrical pressure transducers with simplified hydromechanical valves and we believe this is still acceptable for afterburner fuel scheduling controls where the reliability requirements are less stringent than for main engine control.

For a helicopter application the Mach. No. and altitude envelope is relatively limited and satisfactory control can be achieved using the Fe/P_1 type of interface, whereas for the Pegasus the operational envelope is wider in scope and a Fe/P_3 interface is preferred. There is a distinct advantage of this type of control for Pegasus because an incipient engine surge, perhaps caused by reingestion of hot gas, at a selected value of Fe/P_3 results in a rapid fall in compressor pressure and this will cause a corresponding reduction in the engine fuel flow and thus minimise the risk of damage to the engine. This action would still occur under electrical control with a separate electrical transducer but the maximum rate of fuel reduction would be limited by the actuator response.

The case for using electrical pressure transducers becomes stronger for the complex military engine where there may be a requirement for up to four metered flow streams to provide for the main engine and multi-manifold afterburner system. The metering schedules for all the flow streams may require a common pressure term which can be supplied from a pressure transducer, duplicated for reliability, and computed in the electronic controllers. This gives a considerable saving in weight and cost of sensing elements.

General Features and Considerations for Interface Design

The electrical sub-unit of the interface, referred to as the actuator, comprises a motor or a combination of motors and these may be of the following types:-

(a) d.c. stepper motor

(b) a.c. induction motor

(c) torque motor

(d) solenoid

The choice of the type involves the following considerations:-

i its failure mode, particularly when electrical power is removed

ii complexity of driver electronics

iii failure mode of driver electronics

iv power consumption and related heat dissipation in power supplies and driver circuits. This affects the size of the electronic control box and its cooling requirements.

v range of operation from minimum to maximum flow demand in terms of angular or linear output movement representing fuel demanded.

vi speed or response requirements to satisfy overall accelerations and also transients for control loop stability.

vii resolution required for accuracy of setting acceleration and steady-state flow schedules.

viii minimum output torque, or force, required to operate fuel valve.

Additionally the actuator may include position transducers and some mechanical devices such as gearboxes or differentials, and inevitably, it has to be decided whether the actuator is to be sealed against fuel or be fuel-immersed. Seals can greatly increase the output force or torque required from the actuator assembly and it is important to allow an adequate output to overcome additional friction and reactive forces in the hydromechanical mechanism of the interface. Prediction of friction due to wear and varying lubricating conditions is difficult, yet an 'overkill' in output can lead to excessive power consumption, heat dissipation, size and weight. If the unit is to run fuel-immersed, compatibility with fuel and fuel-borne contaminant has to be taken into account.

The hydromechanical sub-unit and actuator have to be designed as a whole to give the optimum performance, minimum size and cost for the complete interface unit.

Design disciplines developed for conventional hydromechanical controls are applicable but special attention is necessary to provide minimum reaction forces from the hydromechanics onto the actuator for the reasons given.

Particular preferences

In the three types of interface described in this paper the actuators run fuel-immersed and the stepper motor has been the preferred type of motor because:-

(a) it uses a 'pulsed' signal input which is compatible with the output of digital electronic controllers.

(b) it can be used for control without reliance on a position or velocity feedback. This is particularly relevant to failure modes where the requirement is to avoid engine upward speed runaway.

(c) failures in drive circuits do not give a runaway situation - the stepper motor reacts by running slower or, more frequently, stopping.

Generally a 'fail frozen' or 'fail fixed' action is a feature in digital electronic control specifications at the present state of evolution, but there are cases when failure to a particular state other than 'frozen' is required during certain engine operating conditions. For an Inlet Guide Vane Control a fail-high requirement would favour the use of a torque motor which gives such desirable features as low-weight, low cost, high speed, and low power consumption.

Redundancy Considerations

As we have seen already, when two electronic control channels are used to control one function whether it be a fuel metering control or a variable geometry feature of the engine, the choice of degree of redundancy and the point of consolidation are influenced by the engine application and the reliability requirements appropriate to the function of the control channel.

In a multi-engine helicopter the reliability requirements permit us to use a dual-dissimilar, redundant system in which a main electronic control drives a stepper motor which operates the fuel metering valve in a full control mode, while, after a failure of the main control, an electronic reversionary control drives a similar but quite separate stepper motor. The latter motor operates a separate element of the fuel metering valve to give the same overall metering effect as the main channel stepper motor. The latter motor operates a separate element of the fuel metering valve to give the same overall metering effect as the main channel stepper motor. Thus the interface uses two stepper motors and the consolidation point of the two electronic controls is effectively in the controlled orifice of the hydromechanical part of the fuel control valve. The form of the consolidation (described later), the low friction of the valve and the use of fuel-immersed motors all reduce the probability of common-mode failure effects of the type mentioned earlier.

For a single-engine VTOL application such as the Harrier, where a completely separate hydromechanical manual fuel control is specified, two notable redundancy options are available for a digital electronic control system:-

(a) a single main electronic control channel with automatic reversion to the manual fuel control, i.e. a hydromechanical redundant control

(b) a dual electronic control using duplicate drive to the main fuel control backed in turn by the existing hydromechanical manual control.

The presence of the manual fuel control permits the interface unit defect rate to be improved by using only one motor. The consolidation point in the dual electronic channel option (b), can be upstream of the electro-hydromechanical interface.

For a complex military engine application involving main engine and afterburner control the reliability requirements necessitate the use of dual motor actuators for the main engine fuel control and the exit nozzle area control but not for the afterburner fuel metering controls. For the system evaluation on the Adour engine we built dual-motor actuators for the main engine and exit nozzle controls. In these actuators the consolidation of the control channels was in the actuator part of the interface. For the afterburner fuel metering controls using single motor actuators the consolidation point was in the electronic channels.

Description of Interface Examples

In this section of our paper we describe, in detail, some types of interface actuators which we have already mentioned.

Dual Motor Actuator

Firstly, the dual actuator which we built and ran on the main fuel metering control of an Adour engine and also for the nozzle exit area controller using a full authority digital electronic control system, is shown in section in Fig. 12. The actuator provided

a linear axial output which we used to load an input selection spring of the main engine flow scheduling unit and a similar actuator was used to drive a control spool valve for the nozzle control.

Two independently driven stepper motors of identical basic design were arranged so that the individual rotations of each motor armature were added together in a nut and screw assembly to give the actuator axial output displacement. Motor B drove the screw and motor A, the nut. The nut was restrained from axial travel under normal working loads and rotated within a ball-race housed in the actuator case. The screw could both rotate and move axially. Each motor could give the full output shaft travel if the other motor was held. Motor A was driven by one lane of the electronic system, motor B by the other lane. In normal operation each motor contributed equally to the output travel and in this condition full output travel was achieved by a single revolution of each motor.

Two independent L.V.D.T.'s were used to monitor the output movement.

The motors were of the variable reluctance type and, therefore, had no detent torque. We provided the fail-frozen action by using friction brakes, one for each motor. We designed the brakes to hold the appropriate motor in the event of power being cut off from one motor and full drive being obtained from the other motor. Whilst this gave a continuously parasitic drag on the motors it did provide a simple brake mechanism.

Thus, we had the driving mechanism to consolidate two electronic control channels. Faults were detected by comparing the rotations of the two motors in a bevel gear differential situated between them. Any significant discrepancy between the motor rotations resulted in a movement of the differential drum which caused electrical switches to be operated according to the direction of its rotation and the angular displacement. Operation of these switches indicated the presence of a fault in one of the control lanes.

As mentioned earlier, over 1500 operating hours were obtained on these units and invaluable experience was gained. Problems occurred due to unpredictable friction levels experienced late in the test periods. The effect was to cause random but correlated stalling of both motors. The maximum torque of each motor was not identical and as friction built up the lower torque motor stalled first. The system recovered by switching correctly to single motor operation but the second motor stalled almost immediately and the system then froze the actuator in correct response to an apparent double failure.

We have already mentioned two of the many lessons learned from this experience - consider the external environment very carefully for "common mode" faults which affect both lanes of control and consolidate the lanes as far into the system as possible. There were others.

The instrumentation originally used on the tests was adapted to checking the control performance in terms of engine behaviour. It did not help to identify the mechanism which caused the freezing of the output. Clear understanding of the sequence of events was only obtained after instrumenting the interface unit. We have since developed an on-line recording and analysis system which allows us to monitor a large number of variables and gives us great flexibility and rapidity in dealing with the data recorded on magnetic tape. We use the system to record not only all the running carried out but the control programme in use at the time. Both are stored indefinitely for future reference.

There were also lessons for the design of the interface.

A larger torque margin from the motors would have overcome the friction; alternatively a braking system which operated only when a system failure was registered would have made optimum use of the motor output.

Similar manfunctions occurred due to fuel borne solid contaminant causing excessive stiction in the nut and screw assembly and in the motor bearings. This could be overcome be arranging for better filtration. We concluded that a simpler mechanism was desirable and, in turn, this directed our attention to the design of the hydromechanical units using mechanisms requiring minimal force or torque outputs from the actuator and using rotary rather than linear movements to simplify the translation of the basic motor movement. Our current work includes the evaluation of an actuator using two motors on a common shaft. This gives a simple mechanical arrangement but adversely affects the motor dynamics due to the increased rotor inertia for the active motor.

Helicopter Interface

As mentioned earlier, Fig. 11, shows the interface unit for a helicopter control. Here we propose to use two identical stepper motor/gear box assemblies each driving a complementary part of the fuel metering valve. The 'main' control lane drives one of the motor assemblies which rotates a cam-like plate the edge profile of which is used to form the metering area for the fuel. The plate rotates in conjunction with a metering orifice which in turn can be rotated independently by the other motor assembly driven by the reversionary lane of the engine controller. In normal operation the reversionary motor is held electrically by a fixed power phase pattern applied to its stator, whilst normal control is provided via the main lane and its motor. If a fault occurs in the main lane, control of the engine is obtained through the reversionary lane via the

reversionary motor whilst the main motor is held. The gearing is arranged so that if a fault develops in the reversionary motor lane during normal operation, such that the orifice element rotates, the main control can maintain correct relative position of the cam plate and the orifice.

Each stepper motor assembly is mechanically geared to a resolver to enable the relative positions to be monitored. These resolvers are not shown in Fig. 11.

VTOL Interface

A basic representation of an interface unit proposed for an engine such as Pegasus has completed several hundred hours operation on a Pegasus engine. The actuator part of the unit used a stepper motor, gearhead and resolver and we have arranged this to drive a rack to move a pivot in the hydromechanical mechanism. This unit senses P_3 in the hydromechanics and the stepper motor position sets a Wf/P_3 value.

The complete unit can be operated with a variety of full authority electronic control configurations ranging from a single main lane to a full duplicated arrangement or with varying pre-determined degrees of control degradation in the reversionary lane. A unit of this type has been run not only with automatic reversion to a manual fuel controller with minimal change in engine thrust but also with an existing, well-proven, production manual fuel control which involves an excursion in engine power during changeover. A variant of this unit uses a dual motor assembly.

In contrast to the designs mentioned earlier, the motor in this actuator cannot rotate indefinitely but has positive end-stops. We originally provided excessive compliance in these end stops and this caused the stepper motor to be back-driven as their deflection was restored.

This gave rise to anomalous rotation of the motor. The natural frequency of the motor/end stop system was such that, when the motor was continuously driven against the end stops, the drive pulses were applied at the instant the motor was being back-driven. The motor then continued to be driven but in the reverse sense.

Various forms of anomalous behaviour can also be observed if the motor is under damped. Current drive, unipolar drive and excessive drive power all result in reduced damping and have produced mysterious effects only clearly explained by properly instrumenting the interface unit.

Conclusion

In this paper we have considered redundancy in its various forms and drawn upon our experience of more than 10 years, with redundant digital systems.

We have described bad experience as well as good because each is of value to us.

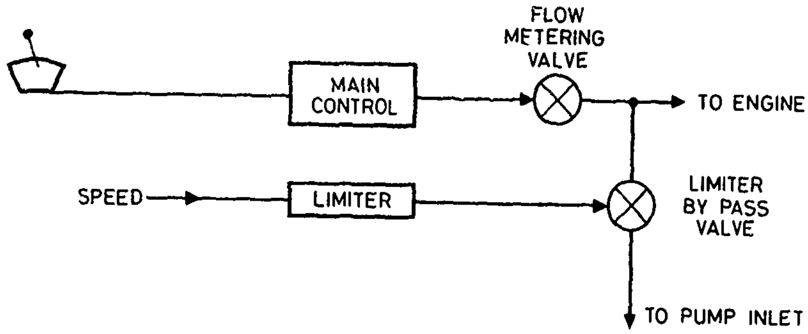
We hope that in this presentation we have gone some way towards answering the 'cri de coeur' of the engine control designer who, after a long, hot and frustrating day on an engine test bed said:

"Electronics is electronics, hydromechanics is hydromechanics, but interfaces are just a can of worms!"

Acknowledgements

The authors wish to acknowledge the work done by their colleagues within Dowty and Smiths Industries Control Limited. Their efforts have led to the accumulation of experience from which this paper has been drawn. Recognition is due also to the support received from M.o.D.(P.E.).

They thank the directors of Dowty and Smiths Industries Controls Limited for permission to publish this paper although the views expressed are entirely their own.

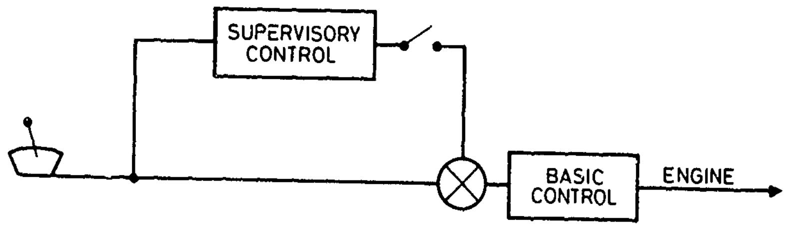


— WIDELY USED ON MANY ENGINES.

— MAY USE TWO VALVES AS SHOWN OR A SINGLE VALVE.

— REQUIRES PERIODIC CHECKS FOR LATENT FAILURE.

Figure 1
Overspeed Limiter



ADVANTAGES

— EASY TO CERTIFICATE.

— ELECTRONIC CONTROL NOT A DESPATCH ITEM.

— SYSTEM AVAILABILITY REASONABLY HIGH.

— BENEFITS OF SOPHISTICATED CONTROL WHEN AVAILABLE.

DISADVANTAGES

— RELIABILITY/MAINTENANCE/WEIGHT BURDEN.

— FULL BASIC CONTROL CAPABILITY NEEDED.

Figure 2
Supervisory System

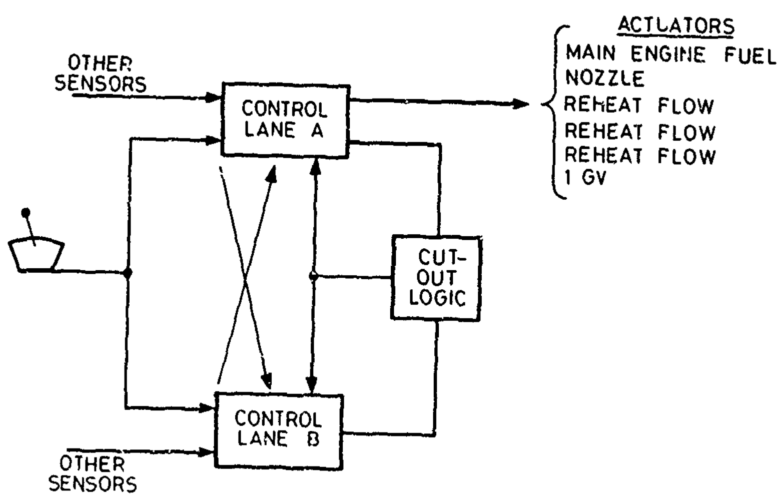


Figure 3
?S50 Engine System

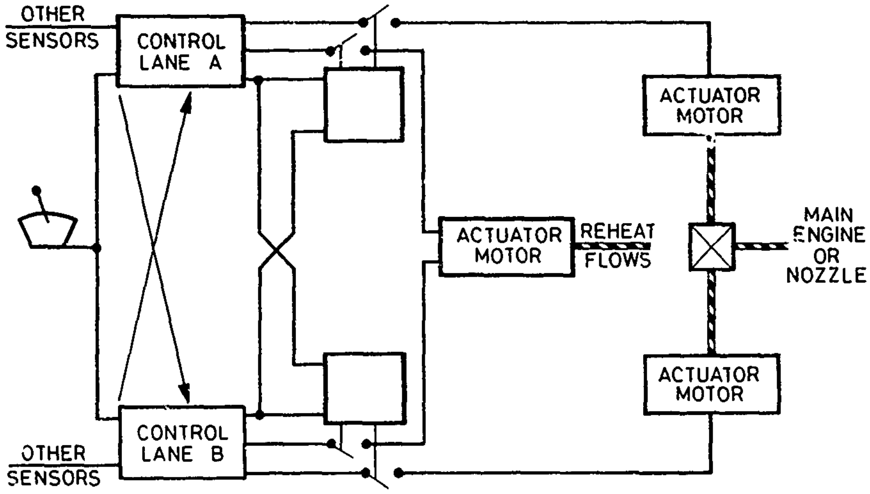


Figure 4
Adour System

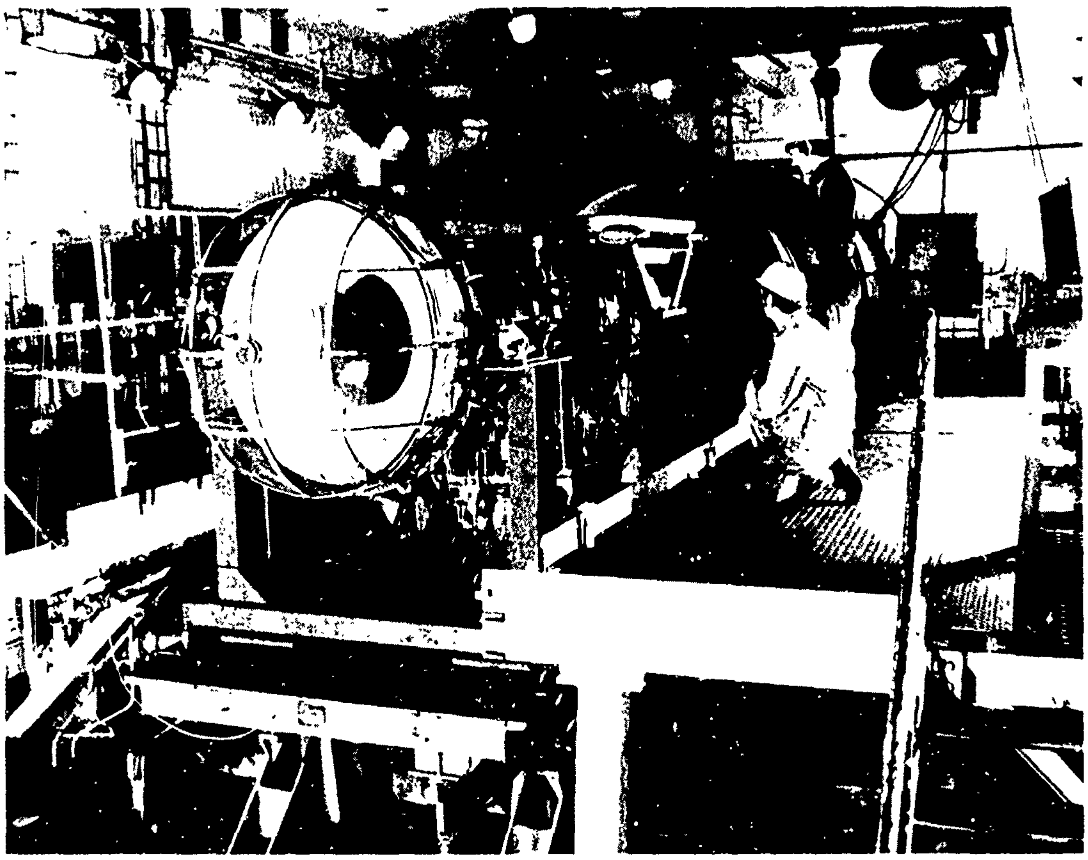


Figure 5
Adour Engine on Test Bed

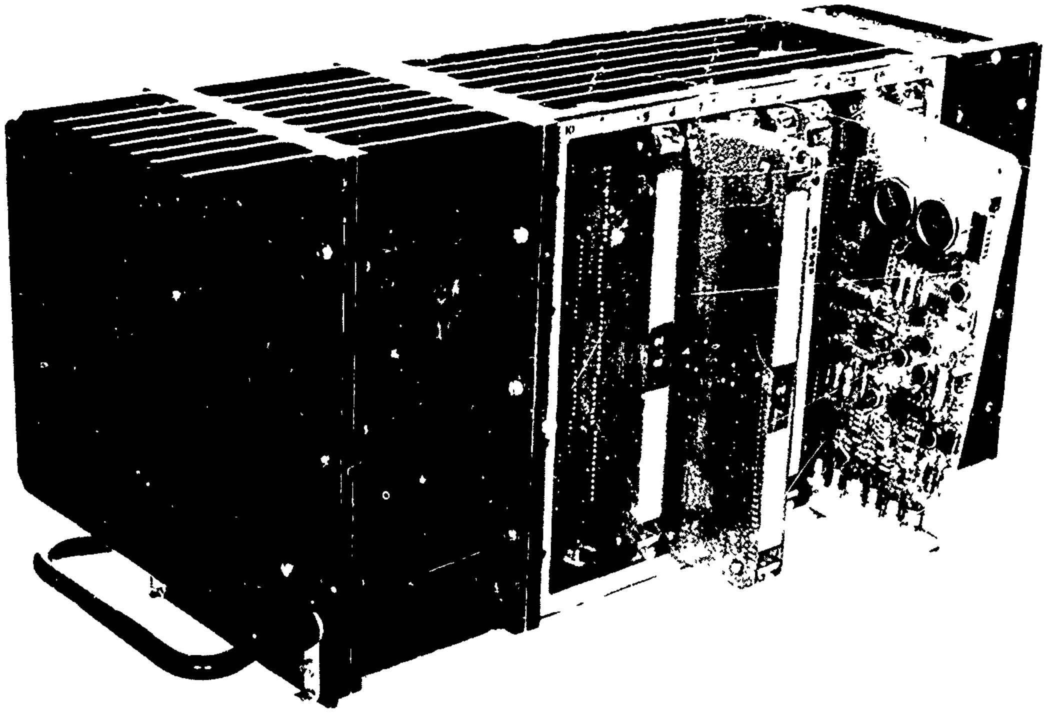
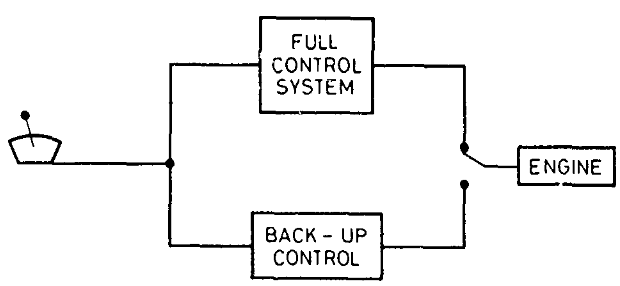


Figure 6
Adour Engine Controller



- MAJOR CHANGE IN PERFORMANCE ON FIRST FAILURE
- CHANGEOVER MAY NEED TO BE AUTOMATIC.
- LEVELS OF SAFETY DEPEND ON SERVICE AND TIMES AT RISK
- FULL CONTROL AVAILABILITY NEEDED FOR DESPATCH
- BACK UP AND HYDROMECHANICAL CONTROL SECTIONS CAN BE SIMPLIFIED.
- TOTAL DEFECT RATE MINIMISED
- COST/WEIGHT REDUCED

Figure 7
Pegasus Engine Control

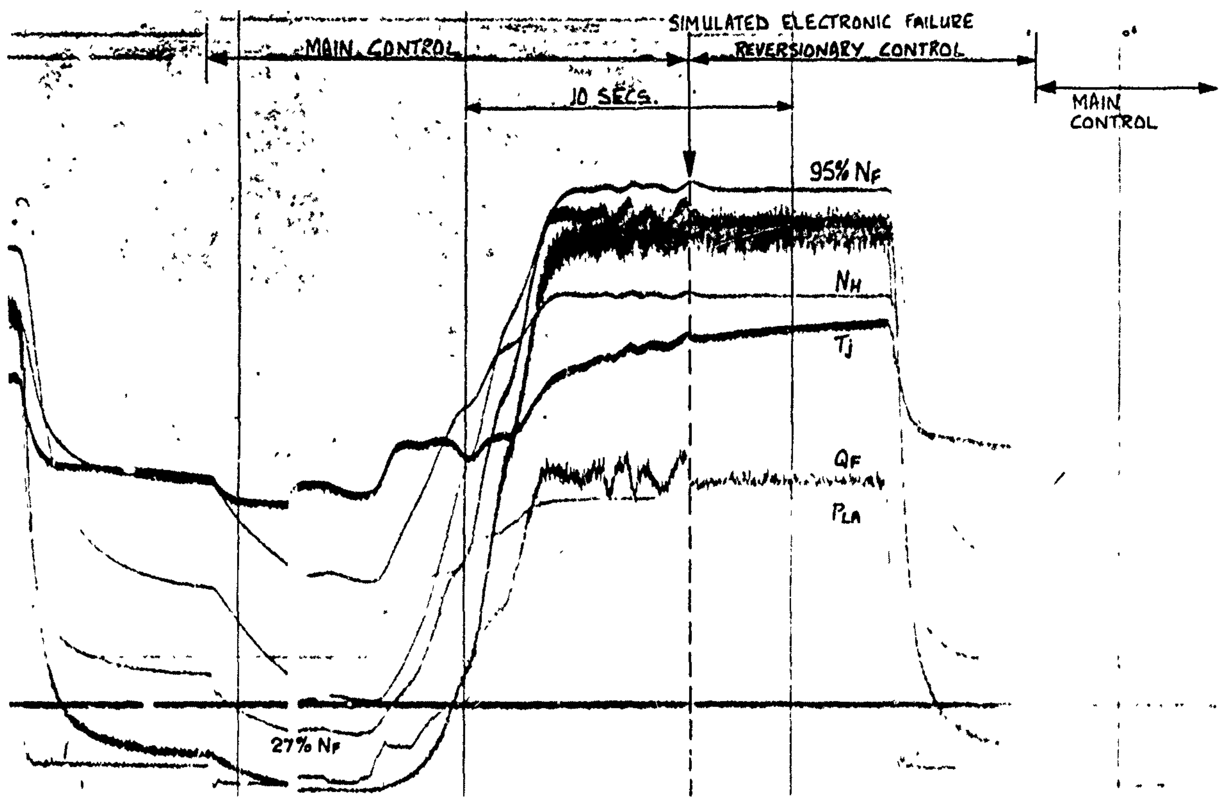


Figure 8
Simulated Failure of Main Electronic Channel with Automatic Change to Manual Reversionary Control at 95% N_F

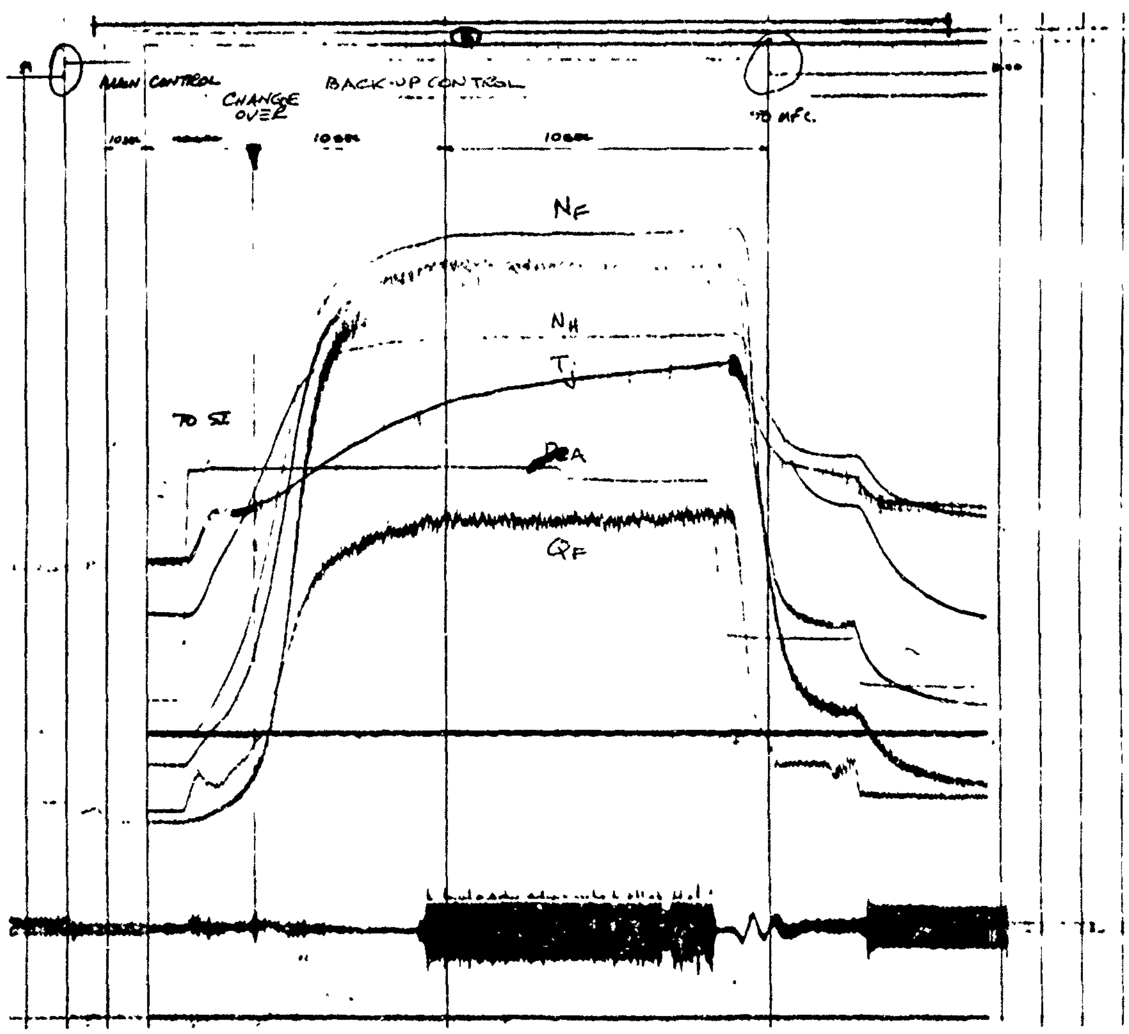


Figure 9
Automatic Changeover During Acceleration

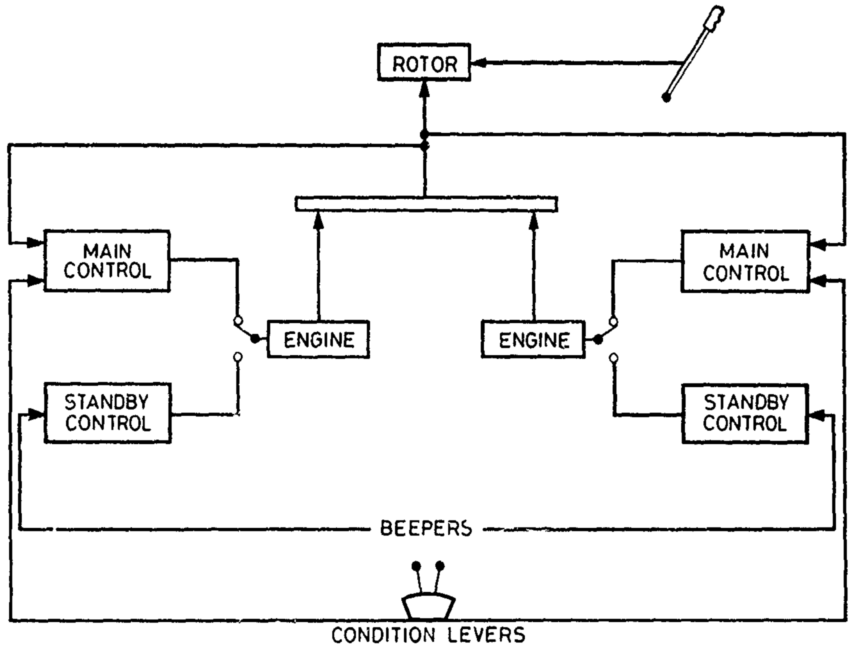


Figure 10
Twin Engined Helicopter System

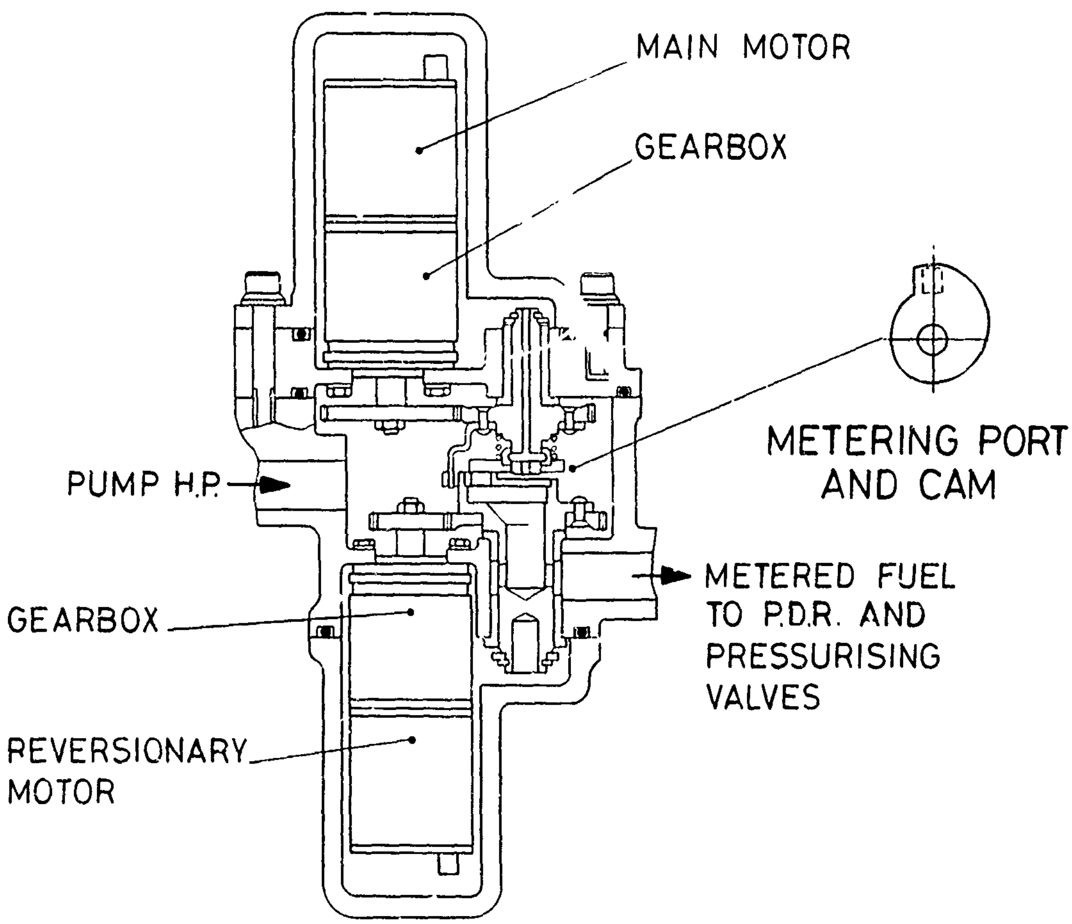


Figure 11
Section through Metering Valve
For Helicopter Fuel Control

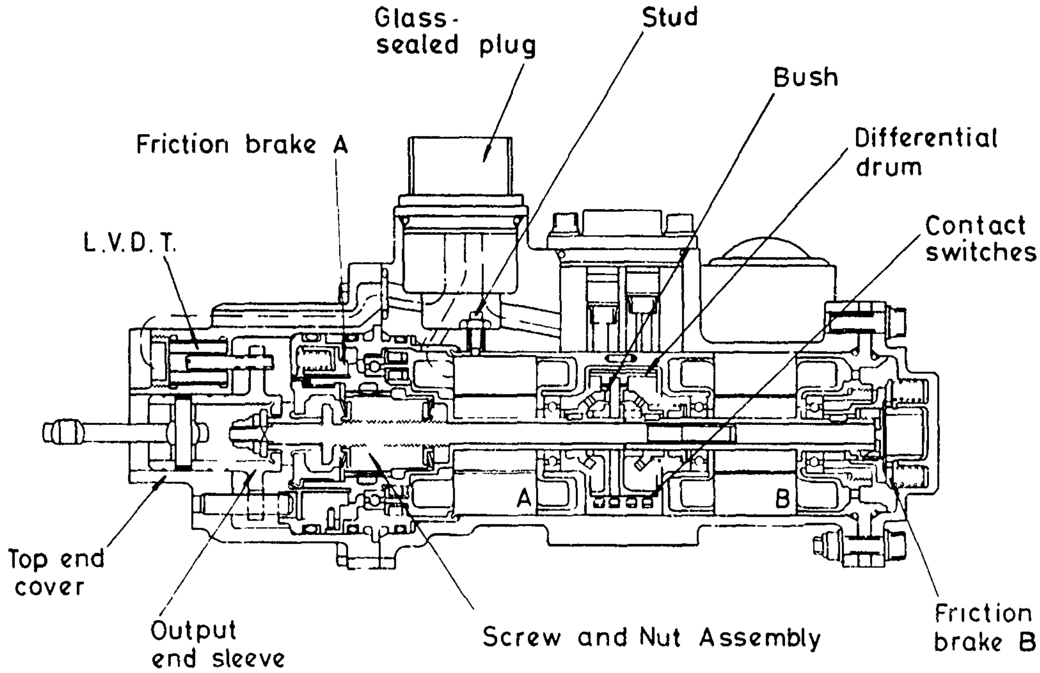


Figure 12
Section through Experimental Dual Motor Actuator

DISCUSSION

G.E.Davies, UK

Keyword: Interfaces. I would agree with your final comment that interfaces are "just a can of worms" and I am thinking more particularly of the input interfaces. This may be because the engine performance people, the control system designers, and the transducers manufacturers do not get together enough to discuss their requirements This then results in non-optimum systems being specified because control system specifications are written around available equipment, and transducer manufacturers do not know what is really required. Can you comment please?

Author's Reply

There is always room for improvement in communications between technologists of all disciplines and this was one of the factors that led Dowty's and Smiths to join forces many years ago. Over the years, there has been steady progress in mutual enlightenment and in-house transducer development evolving from closer liaison with the engine manufacturer and Government technical establishments.

Generally, our requirements for transducers have not been met by "off-the-shelf" items, due to hostile environments, stringent accuracy requirements and special to type interfacing for engine controls. The high technical risk in the new technologies seems to have discouraged investment and interest from the specialised suppliers pending the evolution of a clearer and more positive market.

There are signs that specialist manufacturers outside the immediate engine controls field are becoming more interested and no doubt this will be stimulated more as development of electronic control systems proceeds.

From a physical standpoint, none of the engine parameters are inherently in true digital form. Hence, they all require a greater or lesser degree of modelling in the digitising process Even speed and other frequency signals require a precise hardware time model in the form of a crystal clock or R/C circuit. The essential problem of transducer design is thus the finding of suitable environmentally stable mechanical, hydromechanical or pneumatic models which will transform the analogue engine parameter either into an analogue or digital encoded signal which can be transmitted from the measuring point to the controller To date, the number of such modelling/transmission techniques with adequate environmental capability has been restricted.

Overall control design has thus always required compromises between system requirements transducer locations and current transducer availability and needed close liaison between the various disciplines.

CONDUITE DES MOTEURS DE LA NOUVELLE FAMILLE AIRBUS

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RESUME

La première partie situe le problème général de la conduite moteur, avec les objectifs à satisfaire, et les grands principes retenus.

La seconde partie donne une description de la conduite des moteurs de l'AIRBUS A 300 : commande des gaz, régulation hydromécanique, instrumentation principale moteurs, théorie et choix du paramètre de conduite, systèmes automatiques associés, procédures opérationnelles.

La troisième partie présente les solutions qui sont envisagées aujourd'hui pour les futurs AIRBUS A310, en particulier par l'introduction de régulations partiellement électroniques.

LISTE DES SYMBOLES

ACT : Actuator, servo-moteur d'automanette
ADC : Air Data Computer, centrale anémométrique
AEL : Afficheur EPR limite
ANL : Afficheur N1 limite
CEL : Calculateur EPR limite
CL : Climb, mode de conduite montée
CNL : Calculateur N1 limite
CR : Cruise, mode de conduite croisière
EC : Electronic Control, boîtier de régulation électronique
EGT : Exhaust Gas Temperature, température éjection des gaz
EPR : Engine Pressure Ratio PT7/PT2, rapport de pression du moteur (PWA)
FLX TEMP : Flexible Temperature, température fictive décollage poussée adaptée
FLX TO : Flexible Take-off, décollage à poussée adaptée
GA : Go-Around, remise des gaz
GE : General Electric
HMC : Hydromechanical control, régulateur hydromécanique
M : Nombre de Mach
MCT : Maximum continuous, mode de conduite maximum continu
N1 : Vitesse de rotation de la soufflante
N2 : Vitesse de rotation du mobile haute pression
OAT : Outside Air Temperature, température statique extérieure
PLA : Power Lever Angle, angle du levier des gaz sur moteur
PT2 : Pression totale entrée moteur
PT7 : Pression totale sortie turbine basse pression (PWA)
PWA : Pratt & Whitney Aircraft
RPM : Revolution Per Minute, tour par minute
TAT : Total Air Temperature, température totale
TCC : Thrust Control Computer, calculateur de poussée
TLA : Thrust Lever Angle, angle manette au poste de pilotage
TO : Take-Off, mode de conduite décollage
TRP : Thrust Rating Panel, afficheur de poussée
TT2 : Température totale entrée moteur
Z : Altitude

0. INTRODUCTION

De grands progrès ont été faits en ce qui concerne les moteurs à réactions pour les avions civils des dix dernières années. Les turbo-réacteurs simple flux ou double flux à très faible taux de dilution ont rapidement fait place aux turbo-réacteurs double flux à taux de dilution élevé et à poussée très importante.

En parallèle, les régulations des moteurs basées sur des principes hydromécaniques ont bénéficié d'améliorations notables. Les nouvelles conceptions des systèmes avion ont permis d'accroître encore la qualité des régulations tout en diminuant la charge des équipages, particulièrement par l'introduction des calculateurs de poussée, N1 limite, EPR limite et le couplage de ceux-ci avec le système d'automanette.

Par ailleurs, le développement des technologies basées sur l'électronique et l'électricité tant pour les systèmes avions tels que commandes de vol et commandes de gaz, que pour les régulations en général, a naturellement conduit les motoristes et les avionneurs à introduire au moins partiellement ces techniques dans les systèmes de conduite des réacteurs. Le but recherché dans cette approche est double : économies sur la consommation et l'usure du moteur, et réduction de la charge de travail de l'équipage.

Le but du présent document est d'exposer les principes du système de conduite des moteurs installés actuellement sur l'AIRBUS A 300, ainsi que les solutions envisagées pour la nouvelle famille AIRBUS A 310 et éventuellement A 300, par introduction de régulations partiellement électroniques.

1. PROBLEME GENERAL DE LA CONDUITE MOTEURS

On peut définir la conduite des moteurs d'avion comme étant l'ensemble des systèmes et des opérations nécessaires pour déterminer et pour maintenir sur les moteurs la poussée requise pour chaque phase de vol successive.

L'objectif principal à atteindre est double. Il faut d'une part être sûr de l'obtention de la poussée et ce, avec la précision attendue ; d'autre part, il faut être sûr de ne pas dépasser les limitations du moteur en régimes et en température, ceci afin de conserver la sécurité requise, mais aussi dans le but de préserver la durée de vie des moteurs et de réduire les coûts de leur maintenance.

Les autres objectifs ne sont pas à négliger. Le système doit présenter une grande simplicité de mise en oeuvre et d'utilisation, afin de réduire au maximum la charge de l'équipage. Ceci est de plus en plus important compte-tenu du degré croissant de sophistication des avions actuels et des tendances de nombreuses compagnies aériennes à réduire le nombre de membres d'équipage.

Enfin, les évolutions recherchées par les motoristes et les avionneurs doivent conduire à une réduction de la consommation spécifique et des coûts de maintenance des moteurs.

Ces objectifs sont atteints au moyen de différents systèmes. La commande des gaz permet au pilote d'agir directement mais manuellement sur le régulateur hydromécanique du moteur qui assure le dosage correspondant du débit carburant. En parallèle, le pilote a la charge de surveiller l'évolution des paramètres principaux du moteur (vitesses de rotation des mobiles et température de gaz essentiellement) et doit s'assurer que les limites prescrites ("marques rouges" des indicateurs) ne sont pas atteintes. En complément à ces actions manuelles, le pilote dispose maintenant de systèmes automatiques qui allègent sa tâche. D'une part, le calculateur de poussée détermine et affiche en permanence la poussée limite disponible selon la phase de vol sous la forme d'un paramètre dit paramètre de conduite qui a été retenu par le motoriste comme étant le plus représentatif de la poussée du moteur. D'autre part, le couplage de cette indication de poussée limite avec le calculateur d'automanette permet d'assurer automatiquement par simple pression d'un bouton l'obtention et le maintien sur le moteur de la poussée réelle recherchée.

Nous terminerons ce chapitre de généralités sur la conduite des moteurs par deux remarques essentielles.

La première concerne l'importance du compromis performance avion / durée de vie, donc coût de maintenance du moteur. L'objectif recherché sur ce point ne sera atteint que si le calcul et l'obtention du paramètre de conduite représentant la poussée sont effectués avec une grande précision, d'où l'importance de la qualité des processus de calcul et de la chaîne d'asservissement calculateur de poussée - calculateur d'automanette - commande des gaz - régulateur hydromécanique.

Dans la deuxième remarque, nous voulons seulement rappeler l'importance des décollages et éventuellement des montées effectues en-dessous de la poussée limite. Ces procédures agissent directement sur l'usure du moteur et donc sur le coût de sa maintenance.

2. CONDUITE DES MOTEURS DE L'AIRBUS A 300

L'AIRBUS A 300 est maintenant présenté comme pouvant être équipé de deux familles de moteurs :
- famille CF6-50 (C, C1, C2, C2R) de General Electric
- famille JT9D (- 59A) de Pratt & Whitney.

Les deux moteurs sont évidemment très voisins en ce qui concerne la poussée développée, la constitution interne et le mode de régulation. La différence essentielle qu'il nous est important de connaître pour le sujet traité dans ce document est le choix du motoriste en ce qui concerne le paramètre de conduite représentant la poussée, choix sur lequel nous reviendrons ultérieurement.

Dans le présent chapitre nous nous intéresserons successivement aux sujets suivants : commande des gaz et fonctions du régulateur hydromécanique, instrumentation principale du moteur, choix du paramètre de conduite et théorie de la conduite proprement dite, systèmes automatiques de l'avion : calculateurs de poussée et automanette, utilisation de ces différents systèmes.

Le système de commande moteur est composé d'un ensemble câble - poulie depuis le poste de pilotage jusqu'à un tambour de transfert pour la commande des gaz et de l'inverseur de poussée, et d'un actionneur électrique linéaire pour l'ouverture du robinet HP de carburant.

Le tambour de transfert est installé dans le mât en avant de la liaison principale mât - voilure et transforme un mouvement circulaire en un mouvement linéaire de commande par câble "push-pull" relié au guignol de commande des gaz sur le régulateur de carburant. Le câble chemine sur le côté gauche du carter de soufflante et attaque un ensemble bielle-guignol lié au guignol du régulateur.

Par ailleurs, le tambour de transfert dans le mât est relié au distributeur de commande de l'inverseur de poussée ainsi qu'à la butée d'interdiction empêchant la mise des gaz tant que les obstacles de l'inverseur sont en transit.

L'actionneur électrique linéaire est installé au voisinage du tambour de transfert et est relié au guignol de commande du robinet HP sur le régulateur par une commande similaire à la commande des gaz.

Cette commande des gaz agit directement sur le "levier de puissance" (Power lever) du régulateur hydromécanique dont les fonctions sont les suivantes. En premier lieu, il assure la régulation du régime N2 du mobile haute pression par dosage du débit carburant. Sa fonction secondaire, mais non moins importante, est de préserver le moteur vis-à-vis des limites de pompage notamment pendant les phases d'accélération et de décélération en régime. Ceci est obtenu pour les deux moteurs GE et PWA par l'action combinée du régulateur sur le calage des aubages fixes de compresseur et sur la commande de vannes de décharge

de l'air du compresseur dans le canal de soufflante.

La figure 1 montre le schéma de la régulation hydromécanique du moteur PWA-JT9D

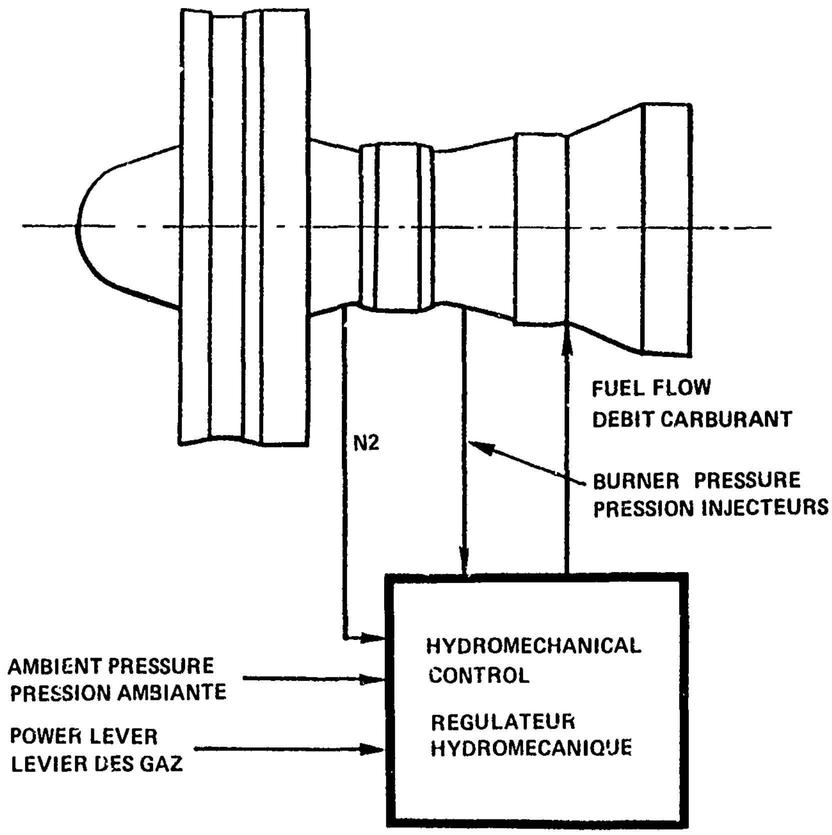

FIGURE 1

REGULATION HYDROMECANIQUE DU JT9D

L'instrumentation principale du moteur comprend les paramètres suivants :
- Rapport de pression sortie/entrée du moteur, EPR : moteur PWA seulement, paramètre de conduite
- Vitesse de rotation de la soufflante, N1 : moteurs GE et PWA, paramètre de conduite du moteur GE
- Température entrée ou sortie turbine basse pression, EGT : moteurs GE (entrée) et PWA (sortie)
- Vitesse de rotation du mobile haute pression, N2 : moteurs GE et PWA
- Débit carburant.

Les indicateurs, au nombre de un par paramètre et par moteur, sont au format 2 ATI et sont situés sur la partie centrale de la planche pilote.

a) L'indicateur EPR comprend les éléments suivants :
- une aiguille indiquant la valeur de l'EPR dans la plage 0,8 à 1,8
- un répétiteur digital à quatre tambours dans la partie inférieure de l'indicateur. Il indique la valeur de l'EPR avec précision dans la plage 0,8 à 1,8. Le dernier tambour correspond à 0,001 EPR
- un index mobile à la périphérie du cadran indiquant la valeur de l'EPR limite
- un répétiteur digital à quatre tambours de la valeur de l'EPR limite dans la partie supérieure de l'indicateur (non automatique)
- un bouton de commande de l'index et du compteur EPR limite (non automatique)
- une chaîne de dépassement fournissant un signal de comparaison entre EPR réel et EPR limite pour le système automanette
- un switch de test qui simule le fonctionnement de l'indicateur pour une valeur particulière de l'EPR.

En mode automatique, c'est-à-dire par couplage avec le calculateur EPR limite, le bouton de commande déjà cité est poussé, l'index mobile de l'EPR limite est commandé par une sortie du calculateur, et le répétiteur digital est masqué. En mode manuel, le bouton de commande est tiré et sa rotation entraîne à la fois l'index mobile et le répétiteur digital qui est apparent. La valeur de EPR limite affichée par l'équipage sur l'indicateur au moyen de ce bouton de commande est relevée sur les courbes de conduite moteur du Manuel de Vol.

b) L'indicateur N1 adapté au moteur GE est très voisin de l'indicateur EPR dont nous venons de parler. Il affiche la valeur de N1 dans la plage 0 à 125 % RPM, avec une précision de lecture de 0,1 % N1 sur le répétiteur digital. Toutes les autres fonctions précédemment décrites pour l'indicateur EPR restent inchangées, de même que les modes d'utilisation. L'indicateur N1 comporte en plus une aiguille d'indication de la valeur maximale atteinte qui est entraînée par l'aiguille principale au-delà de la limite de survitesse.

c) L'indicateur EGT comprend les éléments suivants :

- une aiguille indiquant la valeur de l'EGT dans la plage 0 à 1000° C. Le cadran comprend des plages de couleur jaune et rouge correspondant aux différentes limites d'utilisation,
- un compteur digital à 3 tambours dans la partie inférieure de l'indicateur. Le dernier tambour correspond à 1°C,
- une chaîne de détection et de signalisation des dépassements,
- une aiguille d'indication de la valeur maximale atteinte qui est entraînée par l'aiguille principale au-delà de la limite de température correspondante,
- un switch de test qui simule le fonctionnement de l'indicateur pour une valeur particulière de l'EGT.

d) L'indicateur N2 comprend les éléments suivants :

- une aiguille indiquant la valeur du N2 dans la plage 0 à 120 % RPM. Le cadran comporte un index rouge correspondant à la valeur limite d'utilisation,
- un compteur digital à quatre tambours dans la partie inférieure de l'indicateur. Le dernier tambour indique 0,1 % N2,
- une chaîne de détection des dépassements,
- une aiguille d'indication de la valeur maximale atteinte qui est entraînée par l'aiguille principale au-delà de la limite de survitesse,
- un switch de test qui simule le fonctionnement de l'indicateur pour une valeur particulière du N2,
- un switch à transistor fournissant un signal de fermeture utilisé par le circuit de démarrage pour une valeur particulière du N2.

e) L'indicateur de débit carburant comprend les éléments suivants :

- une aiguille indiquant le débit massique dans la plage 0 à 12.500 Kg/h ou 0 à 27.000 lb/h,
- un compteur digital à quatre tambours dans la partie inférieure de l'indicateur. Le dernier tambour indique les dizaines de kg/h ou de lb/h.

Comme nous l'avons déjà indiqué, le paramètre de conduite choisi par le motoriste est l'EPR pour le moteur Pratt & Whitney et le régime N1 pour le General Electric. Chaque motoriste démontre que la relation entre la poussée et le paramètre qu'il a choisi est conservée avec une bonne précision pour tous les moteurs. Cette démonstration est basée essentiellement sur des essais effectués sur un certain nombre de moteurs. Il est ainsi prouvé que le paramètre choisi représente la poussée.

Sans vouloir intervenir sur les raisons des choix effectués, nous pouvons dire que l'avantage essentiel en faveur du N1 est sa simplicité de mise en oeuvre, alors que la poussée semble plus directement liée à l'EPR.

Etant donné l'existence de la relation poussée - paramètre de conduite, on définit pour chaque phase de vol des courbes de conduite donnant la valeur du N1 ou de l'EPR de façon à obtenir exactement la poussée nécessaire. Six modes de conduite ont été retenus pour représenter les différentes phases de vol : décollage, décollage à poussée adaptée, maximum montée, maximum croisière, maximum continu et remise des gaz. Pour chacun de ces modes, est définie une courbe donnant le N1 ou l'EPR en fonction de la température totale et de l'altitude pression. Chaque courbe est écrêtée à une valeur maximale en-dessous d'une certaine température dite température de cassure ou température de flat rating. En-dessous de cette température, la poussée reste approximativement constante. Au-dessus, la poussée décroît avec la température totale TAT, de façon à conserver toujours une légère marge par rapport à la température d'EGT limite correspondant au mode considéré. Chaque régime est donc défini par deux données :

- une courbe de limitation en EGT qui peut être représentée par un polynôme en TAT de degré inférieur ou égal à cinq,
- une température de cassure (flat rating) définie par un écart par rapport à la température ISA en fonction de l'altitude. Ainsi, pour chaque mode de conduite, la poussée maximale est définie au moyen d'une courbe donnant le paramètre de conduite, semblable à celle schématisée sur la figure 2 à titre d'exemple.

Chaque courbe est établie pour une configuration particulière de prélèvements d'air : aucun prélèvement pour le décollage et le décollage à poussée adaptée, prélèvements pour le seul système de conditionnement d'air pour les quatre autres modes. Pour les autres configurations de prélèvements, des corrections sont apportées au N1 ou EPR. Ces corrections dépendent de la quantité de systèmes alimentés par l'air prélevé sur le réacteur et sont données en fonction de l'altitude.

Le décollage à poussée adaptée peut être utilisé chaque fois que la masse réelle de l'avion au décollage est inférieure à la masse maximale autorisée. Comme cette dernière décroît quand la température croît, il est possible de faire correspondre une température fictive à la masse réelle de l'avion. Cette température est appelée "Flexible temperature" et est donnée pour un aéroport et un type d'avion donnés par la fiche de terrain en fonction de la masse de l'avion et compte-tenu de la TAT (= OAT) locale du jour considéré. La poussée ainsi obtenue est parfaitement adaptée à la masse réelle de l'avion, de sorte qu'en cas de panne d'un moteur au décollage, celui-ci est effectué dans les mêmes conditions de sécurité qu'un décollage normal sans aucune action particulière de l'équipage. Le pourcentage maximal de réduction de poussée en "FLEX TO" est aujourd'hui de 16 % ; les approches nécessaires sont en cours actuellement pour atteindre 25 %.

Remarques :

1°) Les courbes de conduite pour chaque mode sont définies en fonction de la température et de l'altitude à partir des données fournies par le programme de performances du moteur. On prend en compte, dans cette définition, des termes additifs aux valeurs théoriques du paramètre de conduite qui correspondent aux phénomènes suivants : transitoires de régimes en particulier lors de l'évolution thermique du moteur au décollage, présence d'humidité dans l'atmosphère réelle, écarts entre moteur minimal et moteur moyen pour les régimes certifiés.

2°) En cas de panne d'une indication de paramètre de conduite (N1 ou EPR), une conduite manuelle est utilisée en secours au moyen d'un autre paramètre, moyennant généralement la prise en compte de légères pénalités de poussée. Le paramètre de remplacement du N1 est le N2 pour le moteur GE, celui de l'EPR est le N1 pour le moteur PWA. Les objectifs fixés pour la définition de ces courbes de secours sont les suivants :

- être sûr de la poussée réellement obtenue sur les réacteurs,
- être sûr de ne pas dépasser les limitations du moteur.

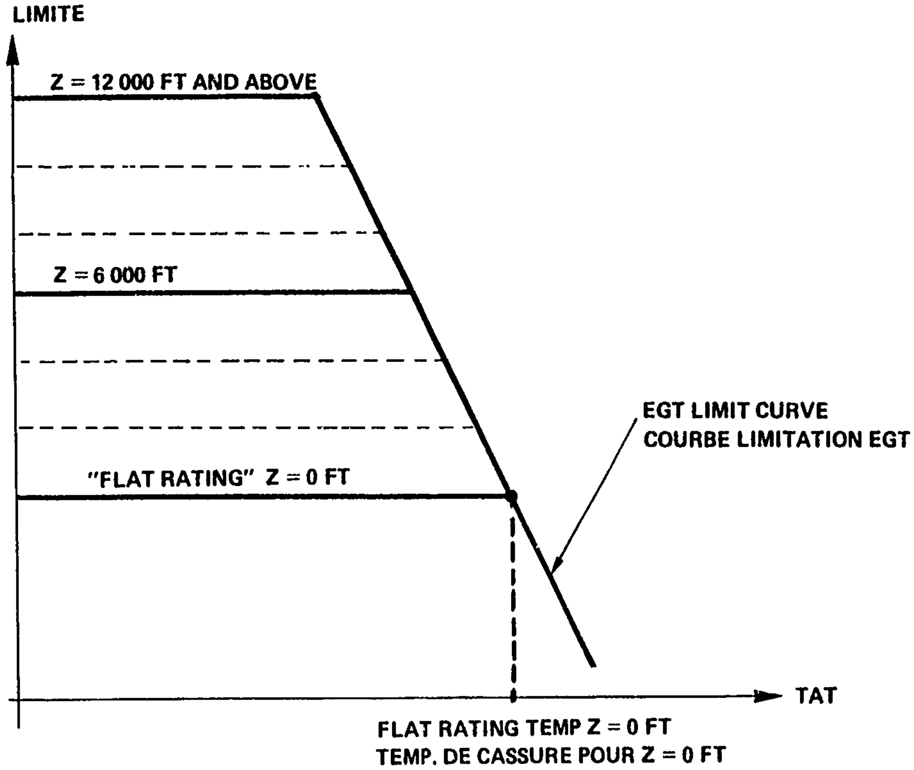

FIGURE 2

EXEMPLE DE COURBE DE CONDUITE : JT9D - DECOLLAGE

Cette théorie de la conduite moteur est mise en pratique dans le manuel de vol de l'avion qui donne le tracé des différentes courbes dont nous avons parlé, ainsi que les corrections nécessaires.
Mais ce calcul manuel est également prévu dans le système automatique comprenant le calculateur de N1 ou EPR limite et l'afficheur correspondant. Ce calculateur (CNL ou CEL), de technologie digitale, assure les fonctions suivantes :

- calcul du N1 ou EPR limite à partir des paramètres de vol (altitude - pression, mach, température totale) et des conditions de prélèvements d'air, pour les différents modes. Pour celà, le calculateur possède en mémoire les différentes courbes d'EGT limite sous forme de polynômes, ainsi que les valeurs des températures de cassure ;
- calcul de la TAT à partir des signaux délivrés par la sonde avion et compte-tenu des diverses corrections à leur apporter (étalonnage, échauffement pour dégivrage) ;
- élaboration d'un signal d'erreur entre la valeur du N1 ou EPR limite et les valeurs réelles N1 ou EPR des moteurs pour utilisation par le calculateur d'automanette.

L'afficheur de N1 ou EPR limite (ANL ou AEL), de format 3 × 5 ATI est situé sur la partie centrale de la planche de bord et comprend :

- Un clavier à touches lumineuses, chaque touche correspondant à un mode de conduite : TO, FLX TO, GA, MCT, CL, CR. Chaque touche comporte deux parties : la partie inférieure affiche en permanence l'inscription du mode en blanc ; la partie supérieure est constituée par un voyant qui s'éclaire quand le mode correspondant a été choisi et est correctement pris en compte dans le calcul (voyant vert pour tous les modes sauf pour le FLX TO où il est ambre). Il y a également une touche de test.
- Un ensemble d'affichage de N1 ou EPR limite, composé de quatre afficheurs lumineux donnant la valeur du paramètre limite calculé. Le dernier afficheur correspond à 0,1 % RPM N1 ou 0,001 EPR.
- Un ensemble d'affichage de la TAT, composé de deux afficheurs lumineux du même type que le précédent ainsi qu'un afficheur supplémentaire pour le signe, qui indique la température totale TAT en provenance de la sonde avion via le calculateur. Le dernier afficheur correspond à 1°C.
- Un clavier de roues codeuses permettant d'afficher manuellement la température fictive utilisée pour le décollage à poussée adaptée à partir des données de la fiche de terrain, comme cela a été expliqué précédemment.

En complément au système automatique de calcul du N1 ou EPR limite, le couplage avec le système automanette a été réalisé sur l'A300. A l'origine, l'automanette a été conçue pour le mode "SPEED", c'est-à-dire pour l'obtention et le maintien d'une vitesse avion donnée, essentiellement en croisière et pendant les phases d'attente et d'approche. Par la suite, compte-tenu des possibilités du calculateur d'automanette et des informations utilisables depuis le calculateur de N1 ou EPR limite, le couplage entre les deux calculateurs a permis de développer un nouveau mode appelé mode "N1" ou "EPR". Quand celui-ci est utilisé, l'automanette assure l'asservissement du N1 ou de l'EPR réel des moteurs avec le N1 ou l'EPR limite. Ainsi, le système d'automanette a pris de l'importance puisqu'il est utilisé soit en mode "N1" ou "EPR", soit en mode "SPEED" dans toutes les phases de vol sauf la descente. Pour mémoire, nous signalerons que ce système agit sur un seul servomoteur, chaque réacteur étant "aliгné" indépendemment au moyen de deux embrayages.

Pour terminer ce paragraphe sur les calculateurs, nous parlerons brièvement des tests du calculateur N1 (EPR) limite. D'une part, il possède une autosurveillance permanente qui est particulièrement aisée grâce à la technologie digitale ; ainsi 97 % des circuits sont autotestés. De même, l'autosurveillance couvre divers éléments extérieurs : régimes et EPR des moteurs, données en provenance de la centrale anémométrique, circuits d'interface, liaison digitale calculateur - afficheur, etc... Les défauts ainsi détectés sont indiqués sur la face avant de l'afficheur et envoyés sur le message digital vers les utilisateurs. Par ailleurs, le bouton poussoir de test situé sur la face avant de l'afficheur N1/EPR limite permet d'effectuer des tests complémentaires dont les résultats sont transmis vers les fenêtres N1/EPR limite et TAT : la présence de six "8" montre le bon fonctionnement de l'ensemble, d'autres configurations d'affichages permettent de localiser en grande partie l'origine de la panne : ADC, sonde TAT, ANL/AEL, liaisons, etc...

La figure 3 donne un schéma récapitulatif sommaire de l'ensemble des systèmes décrits, schéma qui correspond au moteur CF6-50.

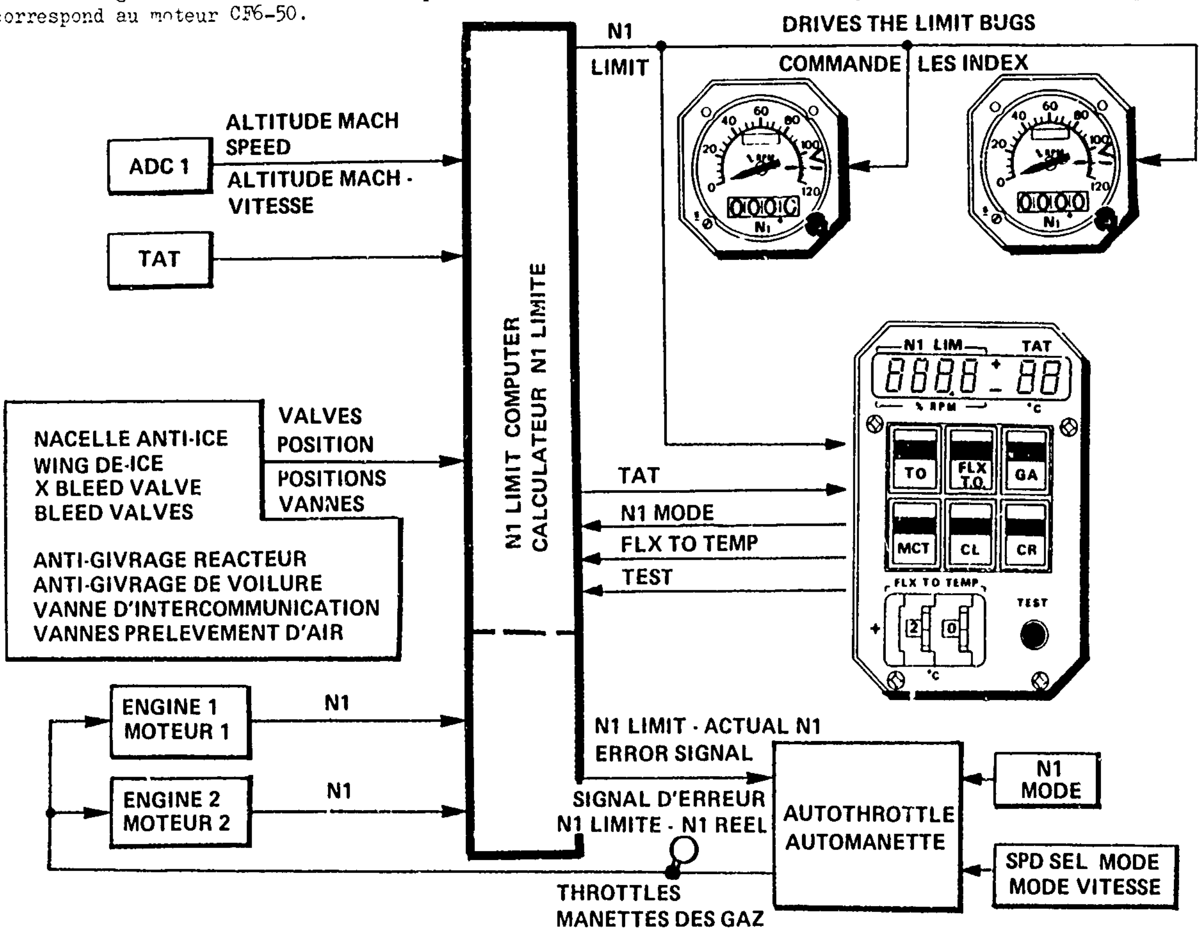

FIGURE 3

CF6-50 - SCHEMA D'ENSEMBLE DU SYSTEME N1 LIMITE

Pour terminer ce chapitre consacré à l'A 300, nous parlerons de l'utilisation des systèmes de conduite moteurs que nous venons de voir, laquelle peut se décomposer en trois modes :

- mode manuel
- mode automatique sans automanette
- mode automatique avec automanette.

1°) Le mode manuel est celui qui est le moins utilisé ; il constitue le secours du calculateur de poussée limite en cas de panne de celui-ci. Dans ce cas, le pilote lit sur les courbes de conduite données dans le manuel de vol la valeur du N1 ou EPR limite en fonction du mode de conduite, de la TAT, de l'altitude et de la vitesse avion. Il peut effectuer les corrections dues aux prélèvements d'air et utiliser la méthode de la température fictive pour les décollages à poussée adaptée. Ayant déterminé la valeur du paramètre limite, le pilote affiche cette valeur sur les index des indicateurs N1 ou EPR comme cela a été indiqué précédemment puis pousse les manettes de gaz jusqu'à la coïncidence des valeurs réelles avec les valeurs limites. Les indications digitales permettent d'obtenir la précision requise.

2°) Le mode automatique sans automanette permet au pilote d'éviter la partie calcul et affichage du paramètre limite, laquelle est prise en compte par le calculateur N1/EPR limite lorsque le mode a été sélecté sur la touche correspondante. En l'absence de sélection, l'alimentation électrique étant établie, le type du moteur pour lequel les courbes de conduite sont mémorisées dans le calculateur est indiqué dans la fenêtre N1/EPR limite.

3°) Le mode automatique avec automanette permet d'alléger au maximum la tâche du pilote. Après avoir sélecté le mode de conduite, puis le mode "N1" ou "EPR" sur le panneau automanette, l'engagement du système assure un fonctionnement entièrement automatique, pour lequel le pilote n'a plus qu'à vérifier le bon fonctionnement au moyen de tous les affichages déjà signalés. En cas de panne d'un élément quelconque, l'automanette est automatiquement déconnectée. Par ailleurs, pour certaines phases de vol (attente, approche), le pilote sélectera de préférence le mode "SPEED" qui, lui, assurera le maintien automatique de la vitesse de l'avion. Dans ce cas, le paramètre limite est toujours en mémoire dans la boucle d'asservissement et sert de butée au calcul.

3 - EVOLUTIONS ENVISAGEES POUR L'AIRBUS A 310

L'A 310 qui est une version légèrement raccourcie de l'A 300, doit effectuer son premier vol au début de l'année 1982. Il sera équipé comme l'A 300 de deux familles de moteurs :

- famille JT9D (-7R4C) de PRATT & WHITNEY
- famille CF6-80 (A1) de GENERAL ELECTRIC.

Ces deux moteurs sont très voisins de ceux installés actuellement sur l'A 300, au niveau de poussée près. De plus, ils bénéficient de différentes améliorations techniques étudiées par leur fabricant, et en particulier un système de régulation plus élaboré que l'actuel par l'introduction de l'électronique sur le moteur lui-même. C'est l'intégration à l'avion de ces nouveaux systèmes que l'AEROSPATIALE étudie actuellement en liaison étroite avec GE et avec PWA, afin de proposer une option conduite moteurs améliorée aux compagnies aériennes. Le présent chapitre sera donc basé sur l'état de l'étude tel qu'il est connu actuellement, en juillet 1979. Nous nous intéresserons successivement aux points suivants : problèmes posés par le système actuel de l'A 300, solutions proposées par les motoristes, adaptation de ces solutions au système avion, procédures d'utilisation qui en découlent, avantages que l'on peut attendre de telles évolutions.

Le système de conduite tel qu'il est défini actuellement pour les moteurs GE ou PWA installés sur l'AIRBUS A 300, amène quelques petits problèmes, lesquels sont pratiquement compensés, du point de vue opérationnel, par le couplage réalisé entre le calculateur de poussée et l'automanette.

Le premier de ces problèmes résulte du risque de dépassement des limitations moteurs (régimes, température EGT) qui accompagne les mouvements intempestifs des manettes des gaz, en particulier dans la zone des pleines poussées : décollage et remise des gaz. Ce risque est particulièrement important lors de l'affichage du N1 ou de l'EPR en mode manuel. En effet, la valeur limite du paramètre de conduite doit être atteinte rapidement de façon à assurer l'obtention de la poussée nécessaire le plus tôt possible pendant la phase de décollage ou de remise des gaz ; cette manoeuvre manuelle rapide est difficilement compatible avec le fait qu'il faut prendre des précautions pour éviter tout dépassement de la valeur limite. Nous ne citerons que pour mémoire le positionnement accidentel des manettes de gaz à la pleine butée avant, dont les conséquences sont d'autant plus importantes que la température ambiante est faible. Ces risques existent donc avec une procédure manuelle. Ils existent aussi, mais avec une probabilité beaucoup plus faible en mode automatique pour certains cas de panne du système calculateur de poussée - automanette.

Le deuxième problème rencontré dans la conduite des moteurs de l'A 300 est le phénomène d'évolutions transitoires du paramètre de conduite durant la phase de décollage. Il est dû, d'une part à la variation des jeux entre rotors et stators du moteur lors de la mise en température de celui-ci, et d'autre part à l'effet de la vitesse de l'avion sur la thermodynamique interne du réacteur. Ces deux effets provoquent généralement, à partir du moment où la manette de gaz est fixe, une chute assez sensible du N1 ou de l'EPR durant une minute environ, suivie d'une lente remontée vers la valeur initiale. Cette chute du paramètre de conduite donc de la poussée, doit être prise en compte dans la définition de la conduite par une majoration suffisante de ce paramètre par rapport à la valeur théorique, d'où une réduction de la marge d'EGT par rapport à ce qu'elle pourrait être en l'absence de ces phénomènes.

En plus de cette réduction de la marge EGT, les régulations des moteurs sont telles que le décollage s'accompagne toujours d'une pointe plus ou moins prononcée de cette température. Il en résulte une accélération de l'usure du moteur.

Enfin, le dernier problème qu'entraîne la régulation hydromécanique est sensible du point de vue opérationnel ; il s'agit de la variation de la position manette des gaz pour un régime N1 ou un EPR donné en fonction de la température ambiante. Cette variation qui peut être de l'ordre de 30° TLA pour le moteur GE est schématisée par la figure 4 pour le moteur PWA. Il en résulte une variation très grande, selon la température, de la sensibilité de la manette dans la plage régime ralenti - régime maximum décollage. De plus, le fait que l'angle TLA ne soit pas directement dans la boucle de régulation du paramètre de conduite, compte-tenu des jeux et des tolérances sur les réglages de la commande mécanique des gaz, entraîne de légers décalages entre les deux manettes sur un même avion. Ces différents problèmes relatifs à la manette des gaz doivent être pris en compte par le pilote lorsqu'il assure une conduite manuelle. Ils ont également été considérés pour la définition du système d'automanette.

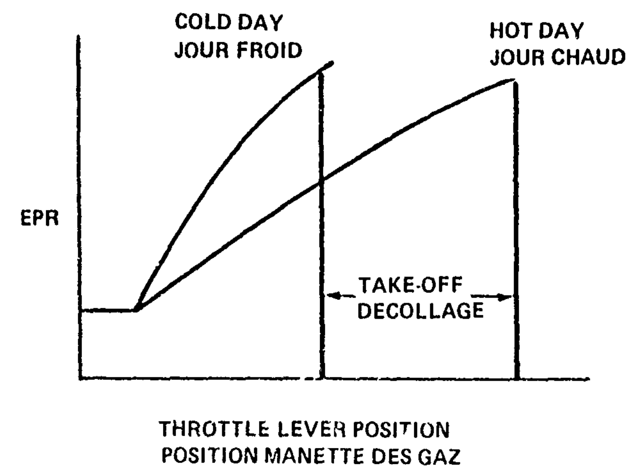

FIGURE 4

REGULATEUR HYDROMECANIQUE DU JT9D - SENSIBILITE MANETTE

Remarque :

Comme nous l'avons déjà indiqué, les critiques ainsi faites au système tel qu'il existe sur A 300 sont très atténuées du fait de la présence de l'automanette utilisée en mode N1 ou EPR ; elles reprendraient leur importance pour un avion ne comportant pas ce perfectionnement.

Afin de pallier ces inconvénients, les deux motoristes GE et PWA ont proposé, pour les nouveaux moteurs devant équiper l'A 310, une amélioration importante par l'adjonction d'un régulateur électronique, installé sur le moteur lui-même, qui agit sur le régulateur hydromécanique. Bien que les définitions présentées à l'origine par GE et par PWA soient légèrement différentes, nous nous baserons sur une définition pratiquement commune vers laquelle les deux motoristes devraient tendre à la demande de l'avionneur.

Le régulateur électronique que nous désignerons par le symbole EC est un calculateur digital, installé sur le carter de soufflante du moteur, qui reçoit des signaux en provenance du réacteur et de l'avion : régime N1 ou EPR, pression et température à la face d'entrée du moteur, position manette de gaz, nombre de mach, altitude-pression, mode de conduite et signaux associés. La figure 5 montre le schéma du système de régulation du JT9D.

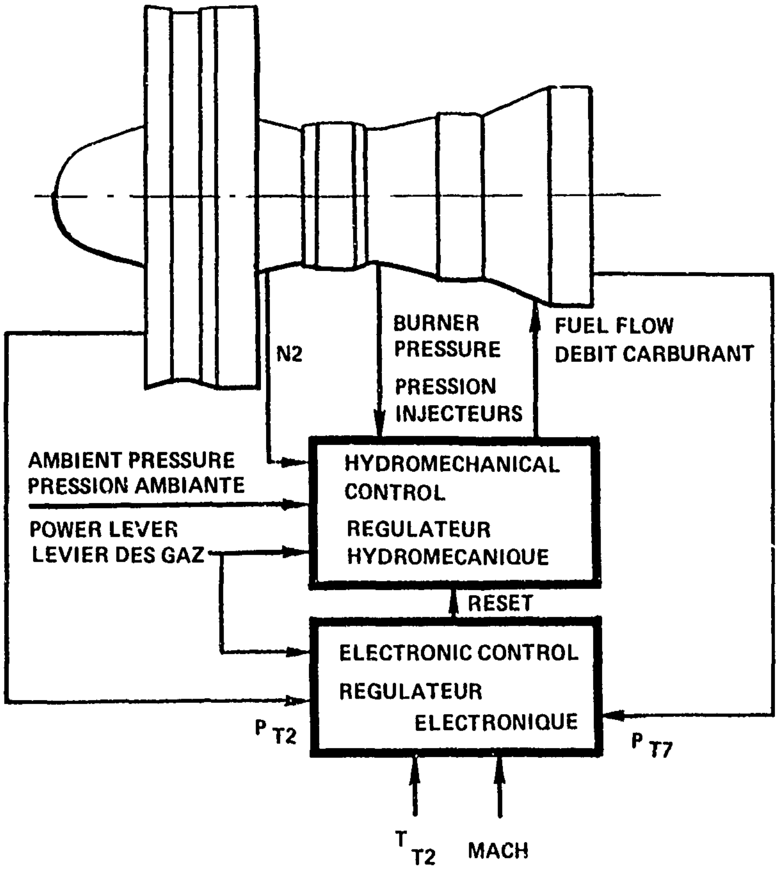

FIGURE 5

SYSTEME DE REGULATION ELECTRONIQUE DU JT9D

Le HMC fonctionne toujours en régulation du régime N2 par dosage carburant. Le EC envoie deux sortes de signaux. D'une part, il agit sur un moteur-couple ajouté au régulateur hydromécanique, qui modifie les lois de régulation à l'intérieur d'une plage d'autorité physiquement limitée. La représentation de l'interaction EC/HMC sous la forme de la poussée en fonction de l'angle manette au poste est donnée figure 6 pour le JT9D. On voit que la position "pleine poussée avant" de la manette donne la poussée nécessaire au décollage sans dépassement, grâce à l'action du EC. D'autre part, le régulateur électronique envoie vers le système avion les valeurs qu'il convient de connaître pour assurer l'affichage et l'obtention du paramètre de conduite.

Le EC, qui possède sa propre alimentation électrique par un alternateur spécial, assure son autosurveillance et fournit les signaux de panne correspondants, à la fois pour les systèmes avion et pour le HMC qui, automatiquement, fixe le signal provenant du EC à sa dernière valeur avant la panne. L'action ultérieure du pilote, qui n'a pas à être immédiate du fait de la présence de la logique dont nous venons de parler, est de déconnecter le E.C. afin de redonner sa pleine autorité à la régulation hydromécanique, et de surveiller le moteur vis-à-vis des limites.

La présence du régulateur électronique assure une meilleure protection du moteur durant les transitoires et contre les manoeuvres intempestives de manettes. Il améliore la sensibilité de la manette des gaz puisque le ralenti et la pleine poussée sont obtenus pour des positions fixes situées aux deux extrêmes de la course du levier, comme cela est montré figure 7. Nous reviendrons ultérieurement sur les avantages apportés par ce nouveau système.

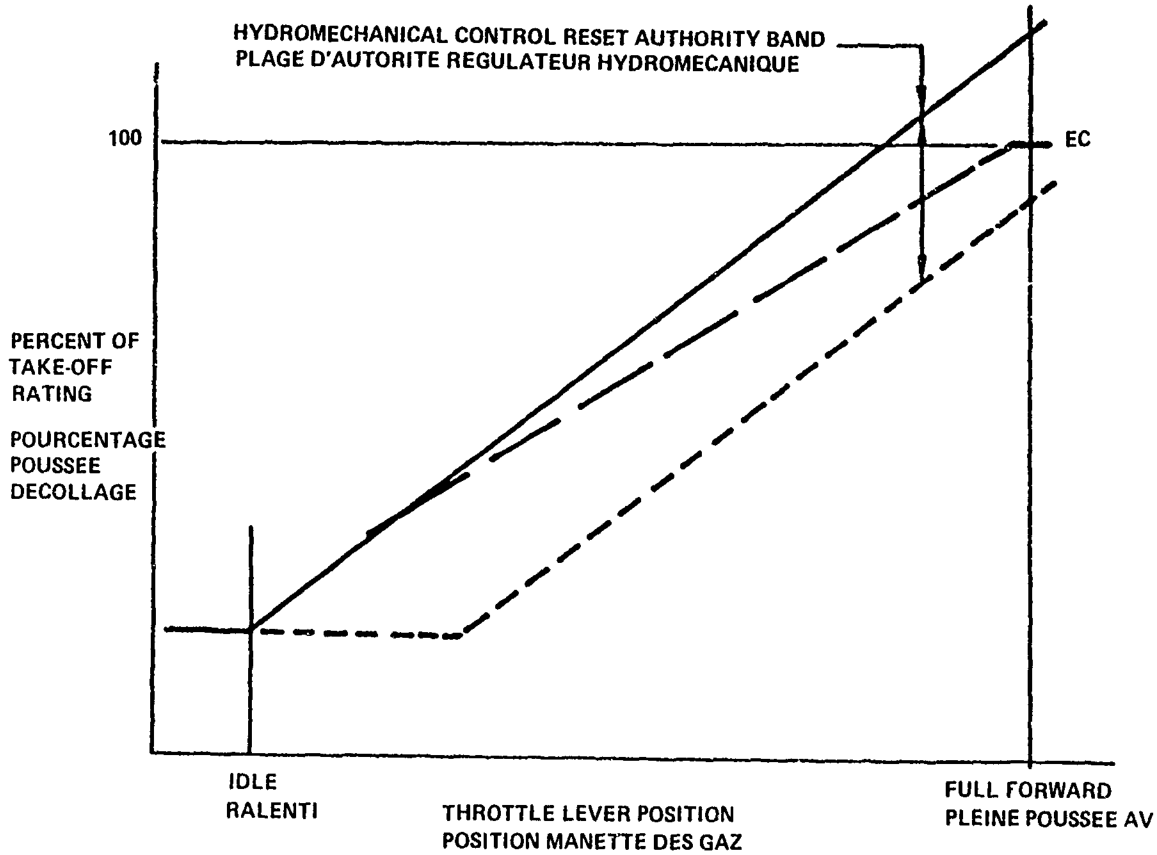

FIGURE 6

JT9D - INTERACTION REGULATIONS ELECTRONIQUE/HYDROMECANIQUE

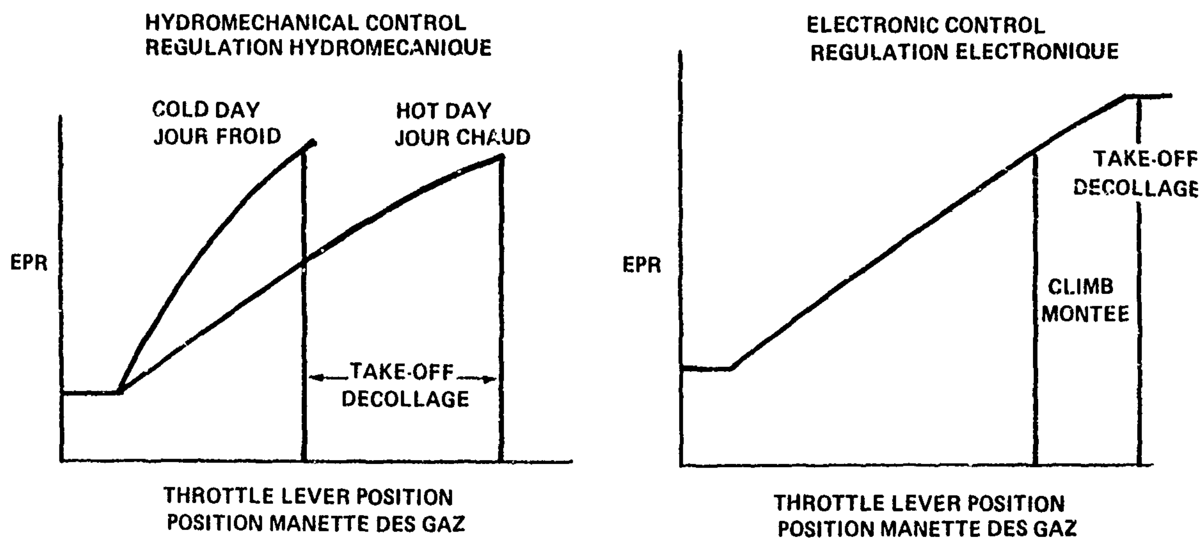

FIGURE 7

REGULATIONS HYDROMACANIQUE ET ELECTRONIQUE - SENSIBILITES MANETTE

Nous allons maintenant examiner les répercussions sur l'avion de la présence de cette nouvelle régulation moteur. Le système de contrôle de poussée de l'A 310 comprend les éléments principaux suivants :

- un régulateur de poussée TCC
- un afficheur de poussée TRP
- deux régulateur électroniques EC, pour moteur 1 et moteur 2
- deux régulateurs hydromécaniques HMC, pour moteur 1 et moteur 2
- deux indicateurs N1 ou EPR, pour moteur 1 et moteur 2.

Les critères de base considérés pour l'intégration avion sont les suivants :

. Le régulateur hydromécanique assure toujours la régulation principale.
. Le régulateur électronique est utilisé pour la conduite moteur (calcul du paramètre limite) pour tous les modes.
. Pour le mode décollage à poussée maximale, les manettes des gaz sont amenées manuellement ou automatiquement jusqu'à la butée pleine poussée avant.
. Pour le mode décollage à poussée adaptée, les manettes des gaz sont amenées manuellement ou automatiquement à la position donnant la valeur nécessaire du paramètre limite ; cette position est en retrait par rapport à la butée.
. Les deux modes maximum décollage et remise des gaz sont confondus du fait de la prise en compte par le EC de l'altitude pression, de la température et du nombre de mach.
. Le EC agit sur les lois contenues dans le HMC, à l'intérieur d'une plage d'autorité limitée.
. Le but de l'avionneur est d'aboutir à des définitions très voisines pour les deux familles de moteur GE et PWA.

La figure 8 donne le schéma de l'ensemble du système avion.

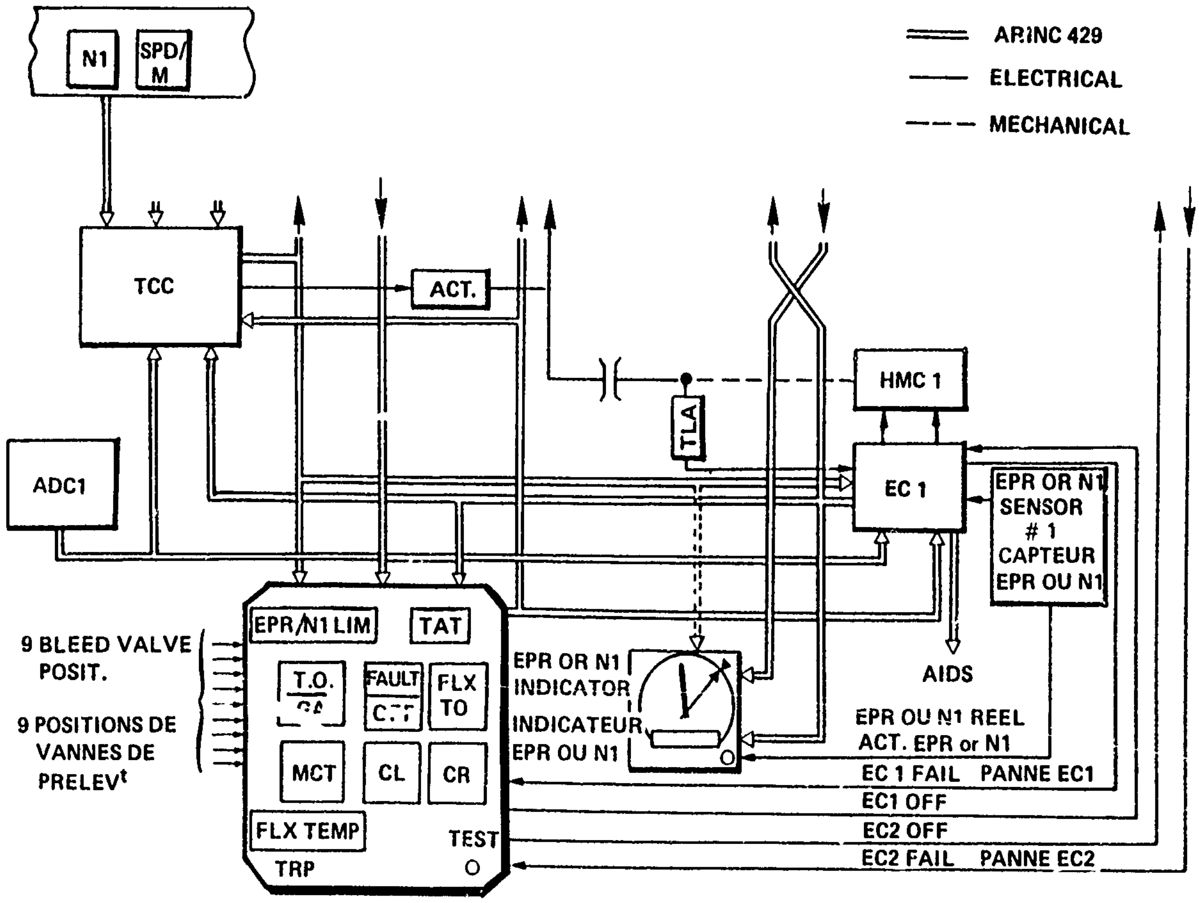

FIGURE 8

A 310 - SYSTEME DE REGULATION DE POUSSEE AVEC REGULATEUR ELECTRONIQUE

Les fonctions des principaux équipements du système sont assurées comme suit :

1°) Le TCC contrôle les modes maintien de vitesse avion et N1 ou EPR. Il effectue les comparaisons nécessaires entre les deux regulateurs électroniques et les deux centrales anémométriques.

2°) Le TRP assure l'affichage du paramètre limite (valeur maximale des deux EC) et de la température totale ; il permet la sélection du mode de conduite et de la température fictive pour le FLX TO : il signale les pannes EC et permet leur déconnexion, il assure la logique des prélèvements d'air moteur pour le calcul des corrections correspondantes dans les EC.

3°) Les EC calculent les N1 ou EPR de conduite pour tous les modes ; ils ferment les boucles de régulation moteur ; ils assurent la transmission des principaux paramètres sous forme digitale.

4°) Les indicateurs N1 ou EPR affichent les paramètres de conduite :

. N1 ou EPR réel sur une aiguille et sur un répétiteur digital à quatre tambours,
. N1 ou EPR limite sur un index périphérique,
. N1 ou EPR dit "de commande" sur une deuxième aiguille ; cette valeur est la transcription en N1 ou en EPR du TLA, elle suit donc sans aucun retard toute variation même rapide de la manette des gaz.

Le fonctionnement général du système est le suivant. Selon le mode de conduite sélecté sur le TRP, le régulateur électronique calcule et transmet pour affichage la valeur du paramètre limite ; la poussée est obtenue par déplacement manuel ou automatique de la manette des gaz de façon à égaler l'indication de commande (N1 de commande, ou EPR de commande) avec la valeur limite. Comme nous l'avons déjà indiqué, le maximum décollage est obtenu avec la manette en butée, les autres modes par des positions intermédiaires mais restant chacune à l'intérieur d'une plage très réduite. Les régulateurs électronique puis hydromécanique referment la boucle d'asservissement en égalant le paramètre réel du moteur au paramètre de commande et par conséquent au paramètre limite. La schématisation de la boucle de régulation entre le TCC, le TLA et le EC au moyen du N1 ou EPR de commande et du N1 ou EPR limite, est présentée figure 9.

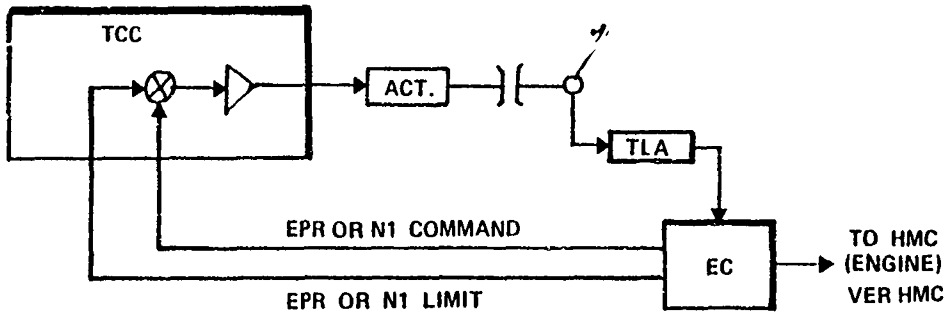

FIGURE 9

A 310 - REGULATION AUTOMATIQUE DE LA POSITION DE LA MANETTE DES GAZ

L'enchaînement des opérations à effectuer par le pilote pour un décollage à poussée adaptée par exemple, en mode automatique, est donc le suivant (cf. figure 8) :

1°) Bouton poussoir de mise en service du EC sur la position "ON" (position normale)
2°) "FLX TO" sélecté sur la touche correspondante du TRP
3°) Température fictive choisie affichée sur le TRP
4°) Mode N1 ou EPR sélecté sur le panneau automanette
5°) Enclenchement de l'automanette
6°) Entre 60 et 80 kts de vitesse avion, vérification que N1 ou EPR réel = N1 ou EPR commande = N1 ou EPR limite.

Cette procédure est voisine mais plus simple pour les autres modes de conduite.

Dans l'éventualité d'une panne de l'un des deux régulateurs électroniques, un voyant lumineux "FAULT" s'éclaire sur le TRP, alarme qui est intégrée dans un bouton poussoir servant à la mise en ou hors fonctionnement des deux EC. La position "OFF" de ce bouton poussoir permet au pilote, sur une panne d'un régulateur électronique, de déconnecter partiellement les deux régulateurs en ce qui concerne leur action sur les régulateurs hydromécaniques, ceci afin de conserver la symétrie des deux moteurs et de continuer à utiliser l'automanette. Dans ce cas, le EC ne s'étant pas déclaré en panne assure le calcul du N1 ou EPR limite, et l'automanette asservit le N1 ou l'EPR réel sur ce N1 ou EPR limite.

Pour résumer les différentes configurations opérationnelles pouvant se présenter en mode N1 ou EPR, nous dresserons le tableau suivant :

a) Fonctionnement normal sans panne
   - Le TRP affiche la plus grande des deux valeurs du paramètre de conduite venant des deux EC, à condition que l'écart entre ces deux valeurs soit inférieur à une limite donnée.
   - Les manettes sont asservies par comparaison entre N1 ou EPR de commande et N1 ou EPR limite.

b) Panne de un EC
   - Le TRP affiche la valeur du paramètre limite venant du EC en bon fonctionnement.
   - Les manettes sont asservies par comparaison entre N1 ou EPR réel des moteurs et N1 ou EPR limite.

c) Panne du TRP
   - Le TRP affiche un drapeau d'alarme.
   - Les manettes sont amenées manuellement à la position donnant le paramètre limite lu sur les courbes du manuel de vol.

d) Panne du TCC
   - Le TRP affiche la plus grande des deux valeurs du paramètre de conduite comme en fonctionnement normal.
   - Les manettes sont amenées manuellement à la position donnant le paramètre limite affiché sur le TRP.

Nous signalerons brièvement la présence d'un système de gestion de vol (Flight Management System), qui permet d'optimiser le vol sur certains critères particuliers, par exemple consommation carburant minimale, durée de vol minimale, etc... Quand ce système est en fonctionnement, les index périphériques des indicateurs N1 ou EPR sont commandés non plus par les signaux de paramètre limite, mais par les signaux en provenance du calculateur de gestion de vol que l'on appelle N1 but ou EPR but. Le pilote manuellement ou le TCC automatiquement amène les manettes de gaz à la position donnant l'égalisation du N1 ou du EPR de commande avec ce paramètre but. Dans ce mode de fonctionnement, le N1 ou EPR limite est mémorisé dans les calculateurs et sert de protection vis-à-vis de dépassements éventuels.

Nous n'insisterons pas davantage dans ce document sur la surveillance de ces systèmes de régulation de poussée. Chaque calculateur assure son auto-surveillance. En complément, un test intégré utilisable au sol et en vol est possible à partir d'un bouton poussoir situé sur la face avant du TRP. Il permet de détecter et d'identifier une grande partie des pannes pouvant échapper aux différentes auto-surveillances.

Les avantages qu'apportent le régulateur électronique et son intégration à l'avion telle qu'elle a été étudiée peuvent être considérés de trois points de vue :

- les avantages concernant le fonctionnement du moteur proprement dit,
- les avantages obtenus pour la définition du système avion,
- les avantages opérationnels.

Concernant le réacteur CF6-80, le nouveau système apporte une réduction des risques de dépassements des limitations puisque la position manette en butée avant est la position normale du maximum décollage. Il permet d'éliminer les transitoires de régime N1 durant la phase de décollage ; en effet, le régulateur électronique, disposant des signaux de température et pression entrée moteur ainsi que du mach, peut assurer le maintien du régime exactement à la valeur déterminée. Il en résulte une diminution de l'importance de la pointe d'EGT qui survient au cours du décollage et par conséquent un gain sur la marge d'EGT. GE a estimé qu'il peut ainsi gagner 8°C sur cette marge EGT, valeur qu'il traduit en un gain de 1700 heures sur la durée de fonctionnement du moteur.

Le réacteur JT9D bénéficie des mêmes avantages que ceux que nous venons d'indiquer pour le réacteur GE. En complément, le régulateur électronique peut assurer par la prise en compte directe de l'EGT, une surveillance de cette dernière, et donc une meilleure protection vis-à-vis de la limitation correspondante.

Du point de vue de la définition du système avion, la présence du EC permet de simplifier partiellement le calculateur de poussée TCC, du fait que le calcul du paramètre de conduite est assuré pour tous les modes par le EC. La mise en oeuvre du système d'acquisition et d'enregistrement des paramètres de l'avion est améliorée, étant donné que le régulateur électronique fournit un certain nombre de paramètres réacteur sur une sortie digitale ARINC 429. Enfin, la présence de deux EC pour l'avion assure une redondance meilleure que ce qu'elle n'est actuellement sur A 300 : en cas de panne d'un EC, le EC restant en fonctionnement calcule et permet d'afficher le paramètre de conduite. Par ailleurs, le régulateur électronique apporte un avantage supplémentaire pour le moteur PWA en ce qui concerne la chaîne de mesure de l'EPR. En effet, l'installation actuelle du JT9D sur l'A 300 comprend pour chaque moteur, deux capteurs de pressions (PT2 et PT7), deux transmetteurs de pressions, et un boîtier électronique d'élaboration de l'EPR pour envoi du signal vers l'indicateur au poste de pilotage ; la présence du EC supprime tous ces éléments du fait que le régulateur lui-même fournit directement en sortie digitale la pression PT2, la pression PT7, et le rapport EPR.

Opérationnellement, le nouveau système apporte quelques avantages qui sont surtout sensibles en mode manuel : obtention de la poussée pour le maximum décollage et la remise des gaz en positionnant les manettes en butée sans préoccupations de risques de dépassements, réglage plus aisé grâce à la présence de l'indication supplémentaire EPR ou N1 de commande. Le EC permet également d'améliorer la sensibilité de la manette, la plage complète de débattement étant toujours utilisée entre le ralenti et le maximum décollage quelles que soient les conditions ambiantes. Cet avantage s'accompagne d'une diminution sensible du décalage entre les deux manettes. Le dernier avantage opérationnel consiste, en cas de panne simple de un EC, et après déconnexion par le pilote des liaisons des deux EC avec les régulateurs hydromécaniques, à la possibilité de réutiliser l'automanette à partir des informations en provenance du EC restant en bon fonctionnement.

4 - CONCLUSIONS

a) Dans cet exposé, nous avons tout d'abord examiné brièvement les données du problème général de la conduite des moteurs d'avions civils. L'objectif principal à atteindre est l'obtention de la poussée avec un maximum de précision tout en respectant les marges imposées vis-à-vis des limitations du réacteur. Les autres objectifs à satisfaire sont la simplicité d'utilisation et la réduction de la consommation spécifique et des coûts de maintenance.

Ces objectifs sont atteints au moyen de différents systèmes qui peuvent être manuels (commande mécanique des gaz, régulation hydromécanique, courbes de conduite) ou automatiques (calculateur de poussée limite, automanette et couplage des deux).

b) Nous avons ensuite présenté la constitution, le fonctionnement et l'utilisation des systèmes actuellement installés sur l'AIRBUS A 300, qu'il soit équipé de réacteurs GE CF6-50 ou PWA JT9D : commande des gaz, régulateur hydromécanique, instrumentation principale, courbes de conduite, calculateur de N1 limite ou EPR limite, calculateur d'automanette. On aboutit ainsi à trois modes d'utilisation : manuel, automatique sans automanette, automatique avec automanette, les deux derniers seulement correspondant à des configurations normales.

c) La définition des systèmes de l'A 300 étant acquise, nous avons énuméré les différents problèmes posés par ceux-ci qui sont liés essentiellement au principe même de la régulation hydromécanique, laquelle ne tient pas compte des variations de conditions ambiantes. Ces problèmes sont les suivants : risques de dépassements intempestifs, phénomènes transitoires durant le décollage, variations importantes de la sensibilité manette entraînant des décalages entre les manettes d'un même avion ou d'un avion à l'autre.

Connaissant ces imperfections de la régulation hydromécanique, nous avons présenté les solutions proposées par les motoristes (adjonction d'un régulateur électronique affinant, dans certaines limites, les lois de régulations basiques de l'hydromécanique) et leurs répercussions sur la définition de l'avion A 310. Pour cela, nous nous sommes basés sur deux principaux critères : le régulateur électronique du moteur assure le calcul de tous les modes de conduite (N1/EPR limite), les décollages à poussée maximale sont effectués avec les manettes en butée avant.

Les avantages apportés par un tel système concernent la protection du moteur lui-même, la définition du système avion et l'utilisation par le pilote.

d) En conclusion, nous pensons que le système du type installé sur A 300 satisfait pleinement les objectifs recherchés et permet une utilisation opérationnelle aisée, les imperfections inhérentes à ce genre de régulation étant partiellement compensées par la définition du système avion. Les améliorations apportées par l'introduction de l'électronique sur les moteurs de l'A 310 assurent une meilleure protection du moteur, facilitent la tâche de l'avionneur, mais n'apportent pas d'avantages substantiels du point de vue opérationnel par rapport au système classique avec automanette en mode entièrement automatique.

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DISCUSSION

M.J.Joby, UK

Figure 8 shows engine control one (EC1) receiving inputs from ADC1. Would system integrity be increased if the inputs from ADC2 were also available to EC1, or is this provided in practice?

Author's Reply

In Figure 8, the TCC compares data from both ADC1 and 2, and then, in normal operation, the data from ADC1 are sent as primary information to EC1 and EC2.

In case of failure of ADC1 the TCC selects ADC2 and sends these datas to EC1 and EC2

In case of failure of TCC, ADC1 is related to EC1, and ADC2 to EC2.

R.P.Wanger. US

You have shown the future anticipated development of the throttle controls and the engine controls. Do you also anticipate future development requirement for the ARINC 429 data bus?

Author's Reply

For the next 10 years, we think that we can stay with the present ARINC 429 data bus, especially taking into account the definition of the "high speed" bus and eventually the "very high speed" bus.

If there are requirements for future development or improvements of ARINC 429 data bus, AEROSPATIALE will anticipate that.

J.Dunham, UK

In a future system, do you believe thrust rating control should be assigned to the autothrottle or to the engine control computer?

Author's Reply

Understanding that thrust rating control means N1/EPR ratings computations, the author's opinion is that these computations should remain on the aircraft side.

The main reason is that the aircraft manufacturer has to be sure of good correlations between power management curves and engine performances. he has to guarantee the Airlines the total aircraft performances including aerodynamics and thrust.

D.M.Griffiths, UK

Two parameters were described for achievement of thrust management, NL and pressure ratio Pressure ratio is more complex to implement, in your experience do the results justify this complexity?

Author's Reply

EPR is of course more complex to handle, our preliminary experience with A300 shipped with PWA engines shows that the final results are the same as with N1.

thrust correlation approximately same results
reaction time on power setting EPR slower
overshoot effect during take-off less with EPR
lapse rate effect during take-off: more with EPR.

J.F.O.Evans, UK

(1) Incorrect thrust control during critical flight regimes is undesirable. How does the author believe that airlines and aircrew will obtain confidence in such thrust control systems?

(2) If we are relying on a supervisory approach for safety is the permissible thrust loss greater than the maximum required trim?

Author's Reply

(1) In case of failure of electronic control during take-off for instance, fail fixed logic existing within the electronic control ensures automatically that HMC remains on last correct power lever position

No immediate action from pilot is required.

(2) No see Figure 6 of the paper.

D.Stanley, UK

What percentage increase in engine life is anticipated with the use of the A310 system of engine control, and what future improvement is to be expected on Future '1' and Future '2'? Will the engine manufacturer give a guarantee?

Author's Reply

(1) Use of electronic control for A310 engines decreased EGT peak on take-off within a range of 3 to 5°C, and increases engine life on wing by 600 hours or more. (General Electric Information). For future engines, additional increase of life time is expected.

(2) The electronic control is a basic part of the engine, therefore the guarantee the engine manufacturer gives includes electronic control.

J.M.Legg, UK

How is the Turbine Entry Temperature controlled with the A310 supervisory engine control?

Author's Reply

The supervisory engine control is defined for constant EGT ratings and EGT peak protection.

In addition, for the PWA JT9D engine, the EGT is directly taken into account in the control loop.

CONTROL OF ALTERNATIVE ENGINES BY MICROCOMPUTER SYSTEMS

by

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Milan, Italy

ABSTRACT

The paper will present aims and results of the research work carried out in the field of fuel system control in internal combustion engines.

Three cars - FIAT 127, FORD Fiesta and ALFA ROMEO Alfasud - have been provided with a microcomputer to control mixture ratio by means of floating chamber pressure regulation in the carburetor.

A complex feedback control loop adjusts pressure level depending upon exhaust gases oxigen contents. Experimental testing of the device evidentiated the dependence of control system time delay upon rpm along with sensitivity to manifold geometry, sensor positioning, and related engine design details. Implemented control has taken into account rpm in relation with the forecast map of specific engine. Tests have been carried on both at constant rev. speed and in ECE 15 emission test. Engine design parameters and sensor location showed a strong influence on control system performance.

Results evidentiated inherent limitations in control loop efficiency related to the use of exhaust sensors. The closed loop approach looks potentially capable of controlling automative engines in the demanding future operational requisites. Progress is dependent upon improvement in air-fuel mixing techniques and in combustion sensors.

INTRODUCTION

In the last years the use of microcomputer systems to control automative engines spread in the R & D area in order to cope with the demand of more stringent emission standards and - in more recent times - of more efficient fuel consumption (1), (2), (3), (4).

The National Research Council - C. N. R. - of Italy, having sponsored a large research program in Energy Savings (5), supported in the last three years the research work whose results are being in part communicated here in. Partecipants have been the C. N. P. M. - National Research Center for Energetics and Propulsion - of Milan and the Dell'Orto Carburator Company of Seregno, Italy. Aim of the research program was to demonstrate the possibility of microcomputer based control systems for control of carburetor engines in closed loop configuration. By the way the research was also intended to investigate collateral problems in the sensors and in the carburetor and engine design areas.

This presentation will deal with a brief summary of current trends in Alternative Engine Control and a more detailed description of tests carried on and experimental results.

The car system design problem has met the technological innovation of LSI electronic components. As a consequence in the system multilevel design several level objectives have been deeply modified because of the innovation that was to be considered. A large variety of options could also be introduced with a very low additional - cost/option - objective cost ratio. Being still in a very massive evolutionary phase car system design solutions have not yet met a commonly agreed definition in several details. Yet design objectives at high system design level are quite clear and strongly demand for innovation applications, among which chiefly :

- lower fuel consumption,
- lower emission,
- good driveability,
- high reliability,
- high safety standards.

The present development status shows both incertitude in subsystem choice and in optimizing criteria.

As far as alternative engines are concerned, assuming that on - chip microprogrammable circuits and/or the rapidly growing variety of specialised or derived devices will provide the technical answer, the engine controller subsystem is faced by at least two rather distinct development trends, letting apart the problem of option integration. The first one is to build up the system as a diagnostic and controlling device, the second one is to provide only a closed loop regulation. In the first case a heavy processing task and a sophisticated software are envisaged - and a larger set of options can be integrated by the way. In the second case the interaction net within the system design is cut smaller and both limitations and advantages can be forecast.

Our research work was intended to operate in the latter area that is to provide a fuel system by driving a rather crude carburetor by means of a microcomputer based control system provided with a regulation closed loop.

The actuation was performed by evaluating a pressure set point output by the system to the carburetor float chamber - Pressure Control Unit PCU - .

MICROCOMPUTER CONTROLLED FUEL SYSTEM

A Dell'Orto carburetor model FRDA 32 F modified as shown in Fig. 1, was chosen for application of controlled vacuum in the float chamber. Ordinarly the top of carb chamber communicates with the air duct pressure is therefore equal to the one immediatly after air filter - (6), (7), (8) - and - depending upon losses - lower than ambient. By means of connecting carburetor float chamber to a device capable od setting a desired pressure value it is possible to control air/fuel ratio. This kind of approach was selected because of its inherent simplicity and easy applicability to preexistent carb models; in addition Dell'Orto Company had already worked in the area looking at vacuum level variations in carburetor chamber as a mean of copying with altitude modifications in operational environment. Furthermore, this device configuration does not need mechanical actuators in the carb such as needles, varying orifices or others. Contemporary control of several carburetors in multicarburetor fuel systems, a case frequent in Europe, is also allowed by using a single controlled pressure signal to regulate air/fuel ratio. Fig. 2 shows the general arrangement of the controlled engine.

In order to provide a CO feedback signal a conventional CO Bosch tester had been used in the preliminary stages. The response time 7 ÷ 10 s allowed only steady operation control. A Zirconia Oxygen Sensor from Bosch was therefore routinely adopted to run the control loop. The response time of Zirconia sensor varies depending upon the temperature and flow rate of exhaust gases (9); in most cases a time in the 30 to 300 ms band can be expected. For these values of response time, a rather good transient behaviour for the control system could be anticipated if several delays were not present due to the effect of other engine components. In our case we met the following delays :
Electronic delays
a) Analog digital conversion and data acquisition delay - 100 μs -
b) Computational time to compare actual and desired value - 200 μs -
c) Computational time to calculate the pressure value to be set - 7 ÷ 30 ms -
The abovementioned values are depending upon the hardware adopted and upon the software implemented; more sophisticated hardware better matched with software requisites could diminish the total electronic delay till to 1 ÷ 2 ms.

Actuation delays.
A typical response is shown in Fig. 3. The total delay for an intervention through the pressure band limits is about 100 ms. Because of the chocken operation of the electrovalves lower figures are to be expected for smaller interventions; in normal operation 60 ms. is a rather indicative figure.

Carburetor delays.
At 4000 rpm for a step pressure variation in the chamber about 15 ms. are needed to vary fuel flow - (11), (12) - .

Inlet duct delays.
As it has been already evidentiated (11) wall adhesion and spray or film wall - effects in ducts between carburetor and inlet ports slow down fuel flow transients; delay time values are strongly affected by several geometrical and thermofluidodynamic factors in inlet duct configuration. Time delay figures stay above 0. 2 ÷ 0. 3 s even in the most favourable conditions.

Combustion chamber and exhaust port delays.
Slow temperature variations in combustion chamber and in outlet valve ducts affect the exhaust gas chemical composition. Rapid engine rpm transients are therefore followed by slow thermic transients whose time delays occur in seconds.

Zirconia Oxigen Sensor delays.
As previously discussed vary between 30 and 300 ms.

Table 1 shows delays values as a function of our actual development level and improved versions; the figures at the ideal level correspond to the rather optimistic assumption of being able to adopt a sensor to diagnosticate lean or rich combustion by means of knock detection (12), (13). Even in this case a total delay time for the regulating system cannot be lower than 1 s, chiefly due to delays in the inlet duct. This time value is too high to provide for closed loop regulation in rapid engine transients, especially for engines with mechanical gear - shift. Since Zirconia Oxigen sensors or similar exhaust gas sensors depend on thermic transients in combustion chamber and exhaust system it looks like they will never be able to cope with rapid engine transients.

COMPARATIVE TESTS IN THREE PRODUCTION SMALL SIZE CARS

Comparative tests have been run fitting three cars with the PCU control system. Cars were Alfasud from ALFA ROMEO, FORD Fiesta 1. 3 and FIAT 127 1050 cm3. Preliminary tests were intended to define the sampling interval -Δt - to be adopted by the PCU in order to allow a stable regulation loop. It was supposed that, at low rpm, delays in the inlet ducts had to be longer and therefore relations between Δt and rpm was investigated. Plots in Fig. 4, 5 and 6 show relations between Δt and rpm. ΔPv values to be set in the carb chamber to obtain steady state stoichiometric air / fuel ratio is also shown. As it can be easily observed peculiar trends are typical for each car tested as a consequence of differences in design of manifold duct.

The distance of the oxigen sensor from the outlet ports was also different and certainly affected the results : 49 ÷ 58 cm. for Alfasud; 35 cm. for FORD Fiesta and 30 cm. for FIAT 127. While a shorter distance in FIAT 127 could favour lesser Δt values it is not probable that it did affect the reverse trend that Δt values show in FIAT 127 tests as compared to other cars. The inlet ducts in FIAT 127 are integrated into the engine head in an arrangement quite different from the other cars considered. Thermic conditions and fuel - wall interactions are likely to be quite influenced by the design configuration and we consider these experimental data as supporting the ipothesis of a strong sensitivity of the control system in the whole towards manifold duct design. It could be guessed that a higher inlet duct temperature in FIAT 127 at low rpm evaporates almost totally the wall - adhering fuel; at higher rpm the turbolence effect is the main factor for air - fuel mixing and it is shared by the three cars observed giving, by the way, very similar Δt values at high rpm.

Other peculiar phenomena were also evidentiated, in the FORD Fiesta at very low engine rpm the PCU control system was sensitive to drops of fuel from the main jet that could not close perfectly at low rpm. The short inlet ducts in Fiesta were not able to filter the fuel flow noise determined by the drops while the other cars were not sensitive.

RESULTS OF EMISSION TESTS

Constant rpm tests gave very repetitive results. Fig. 7 shows CO and CO2 values versus the pressure regulated in the carburetor floating chamber, ECE 15 emission test have been carried out at different temperature conditions for the engine. A cold cycle is run at initial lubricating oil temperature in the 20 ÷ 30 ° C range. A warm cycle is run at initial oil temperature in the 50 ÷ 55 ° C range.

Several factors influence the overall results. The most affecting parameter is the sensor temperature. Since Zinconia Oxigen Sensors give reliable measurements only at temperatures above 380 ÷ 400 ° C tests in which the sensor was not in proper temperature range - partially or totally - gave poor results.

Modifications to better the system performance were therefore introduced chiefly : exhaust pipes were thermally insulated to stabilize higher temperatures, the electric radiator fan air flow was diverted in order not to cool the exhaust pipes, sensor positioning was modiefied to stay more protected.

Typical results are shown in Fig. 8 were CO CO2 and HC concentrations are plotted. Peaks in the CO concentration are still evident in acceleration regions though largerly inferior to the ones occured without taking care to thermal conditions.

In general the system is capable to control CO concentration within acceptable limits in 5 ÷ 6 seconds HC emissions are fairly good; it must noticed that high peaks occuring in decelerations are present in almost all fuel systems and cannot be eliminated unless the fuel flow is almost totally stopped; in this case yet other inconveniences occur - too lean mixtures, misfirings -.

Numerical values for CO CO2 and HC concentrations are shown in Table 2 for an ECE 15 test on ALFA ROMEO Alfasud car. The results are equal to the ones obtained with very sophisticated traditional carburators.

These results suggest that :

- performance of the control system is capable to outperform traditional carburetors provided further improvements are implemented,
- in the long term the repeatibility of results due to the closed loop control still now gives an edge to the system tested over traditional carburetors.

FUTURE DEVELOPMENTS

A series of considerations can be drown in the areas of.

- Improvements applicable to the system.
- Inherent limits of the system tested.

Improvements under evaluation consider throttle position signal and rpm derivative as possible signals to be used to better control acceleration and deceleration transients. Even with rough analysis a simple map of engine behaviour in fast transients and at low rpm is likely to better actual performances. If in this area further improvements were to be looked after, the importance of the engine performance map could overcome the closed loop regulation philosophy. At present we do not feel this step necessary particularly if shortcomings of this approach are going to be kept in consideration.

A limited mapping anyway is needed for cold starting, fast rpm variations and possibly low rpm operating regions. This mapping does not seem to need selfadjusting diagnostic procedures.

Engine design needs several modifications to better match the control system, chiefly in the areas :

- inlet duct,
- carburetor,
- exhaust system.

Combustion sensors based on the knock detection principle or others promise further improvements for the closed loop systems and appear the most promising.

CONCLUSIONS

The research work carried out in the control of carburators by means of electronic systems has shown the capability of at least equalling the best traditional carburator performances.

The closed loop philosophy of the control system appear potentially capable of coping with desired performances without necessity of sophisticated engine performance mapping.

Improvements in sensors to diagnosticate combustion and/or combinations of actual sensors promise a solid future for the closed loop regulation. These systems will never overcome transient time delay in the manifold inlet duct, as a consequence the response time of the regulation will hardly be less than 0.6 ÷ 0.8 s. Only major advances in fuel air mixing techniques could substantially improve closed loop system response time.

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ASME Paper 75 - WA/Aut - 17.

DELAYS msec	PRESENT	IMPROVED VERSION	IDEAL
ELECTRONICS	30	1	1
ACTUATION	60	30	20
CARBURETOR	15	10	10
INLET DUCTS	500	300	150
COMBUSTION CHAMBER & EXHAUST SYSTEM	2500	?KNOCK DETECTOR? ?10?	
OXIGEN SENSOR	210		

Table 1 - Control closed loop subsystem delays in milliseconds.

Car			Alfasud
Weight			1200 kg
Fly wheel			910 kg
Carburetor			FRDA 32 F
Temperature			22 ^C
Relative humidity			57 %
Oil temperature	start end		56 ^C 86 ^C
Analized volume			1950 l
Emissions:			
HC	2.37 g	=	360 ppm
CO	36.12 g	=	1.69 %
CO_2	416.3 g	=	12.4 %

Table 2 - Chassis dynamometer ECE-15 emission test.

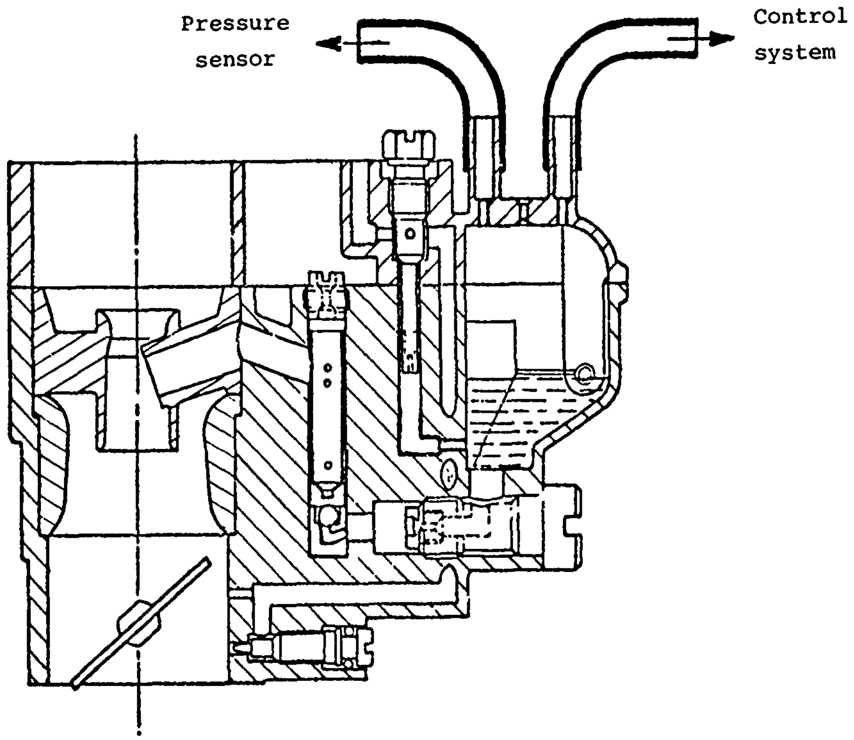


Fig. 1 - FRDA 32 F Dell'Orto Carburetor.

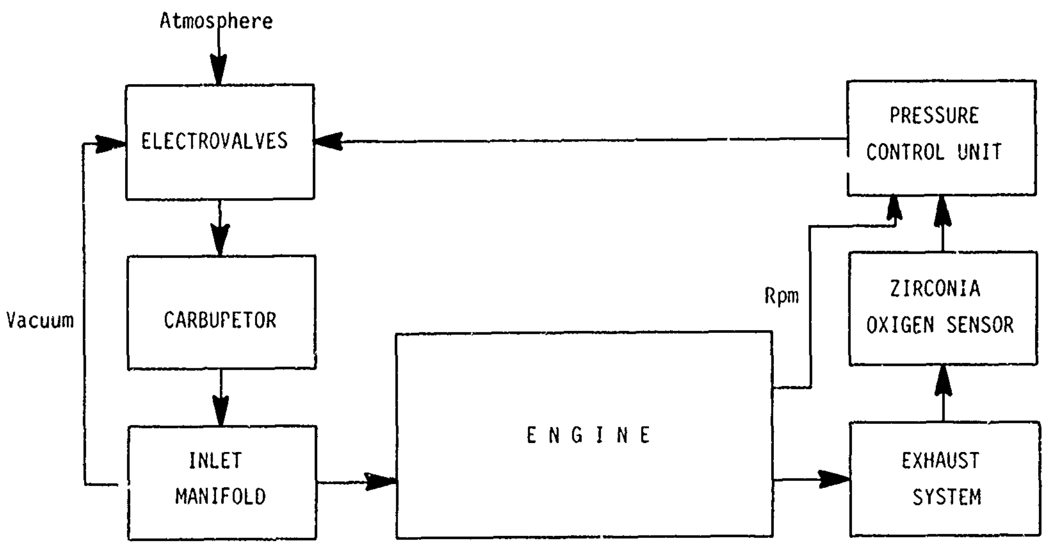


Fig. 2 - Carburetor Closed Loop Control System.

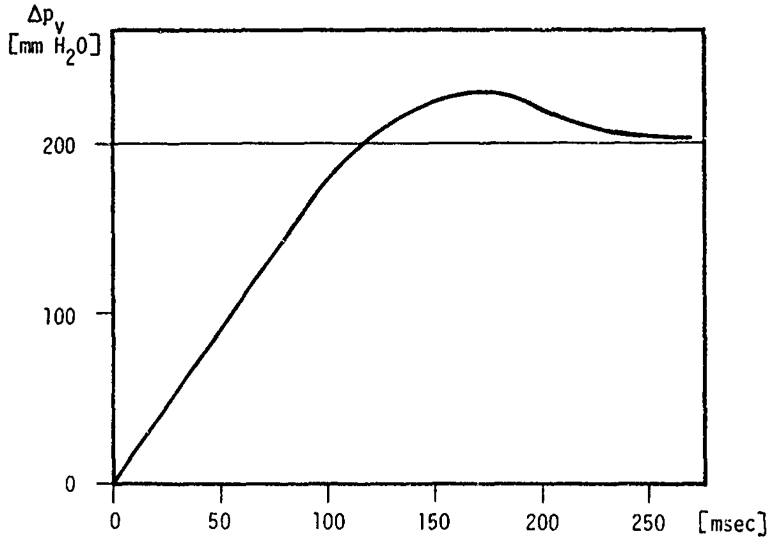
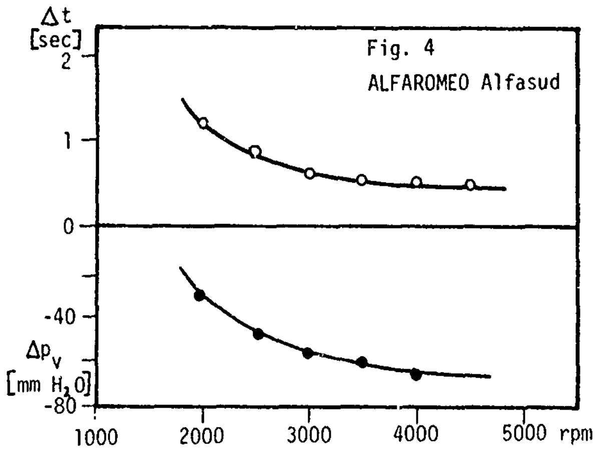
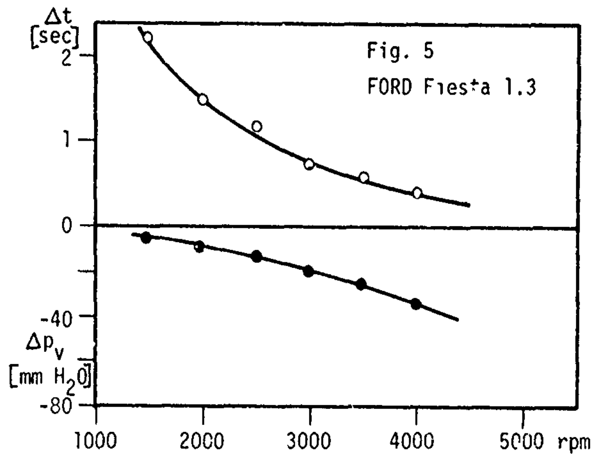
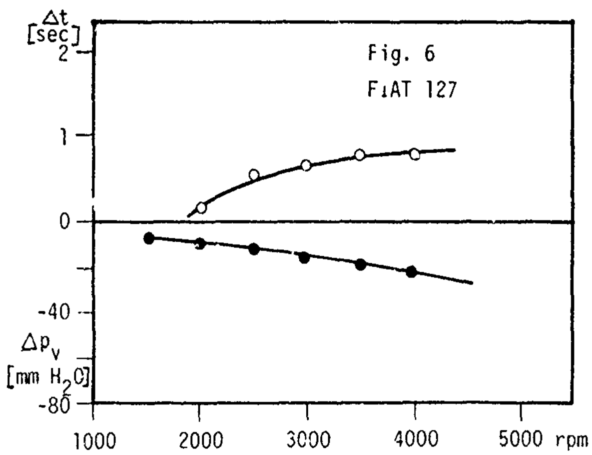


Fig. 3 - Controlled pressure response to a step variation of pressure actuating subsystem.







Figs. 4,5 and 6 - Equivalent sampling interval at stability limit and actuation depression for stoichiometric operation as a function of rpm for the three cars tested.

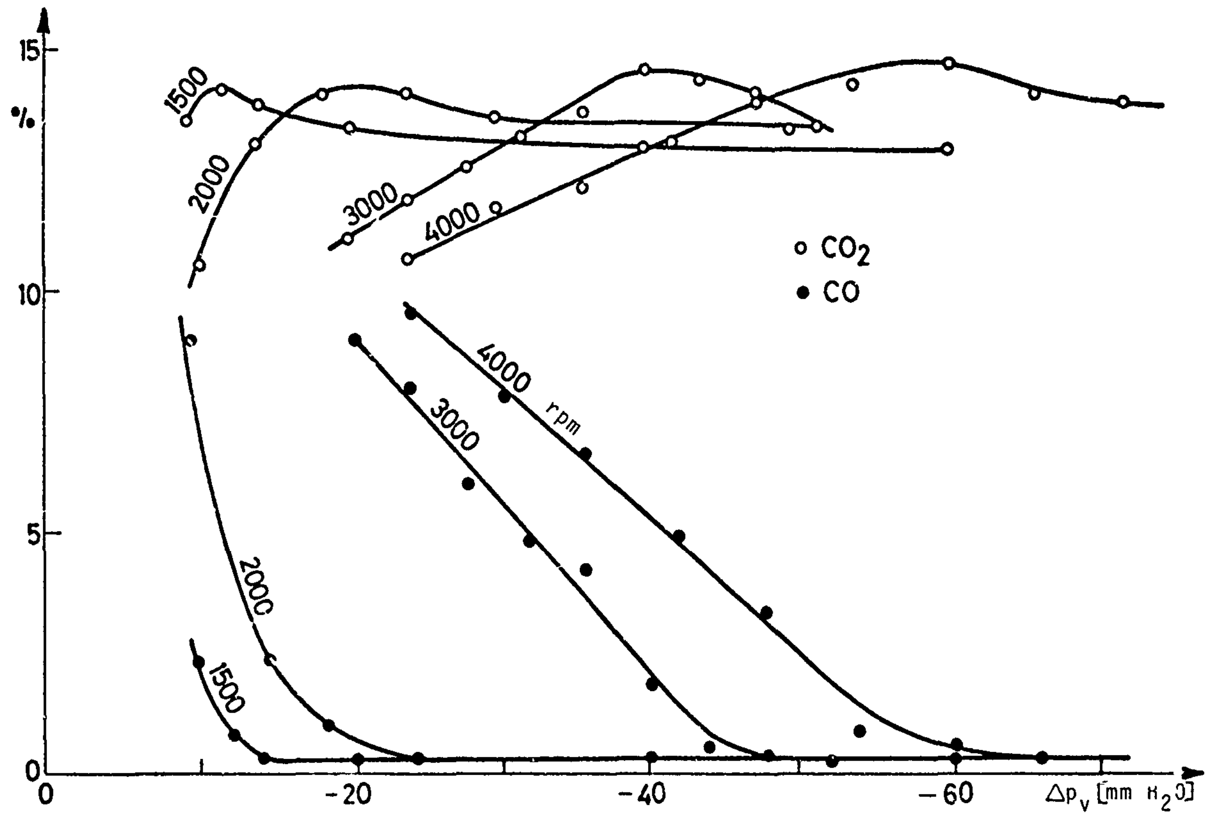


Fig. 7 - CO_2 and CO emissions as a function of rpm and caburetor floating chamber pressure (Alfaromeo Alfasud).

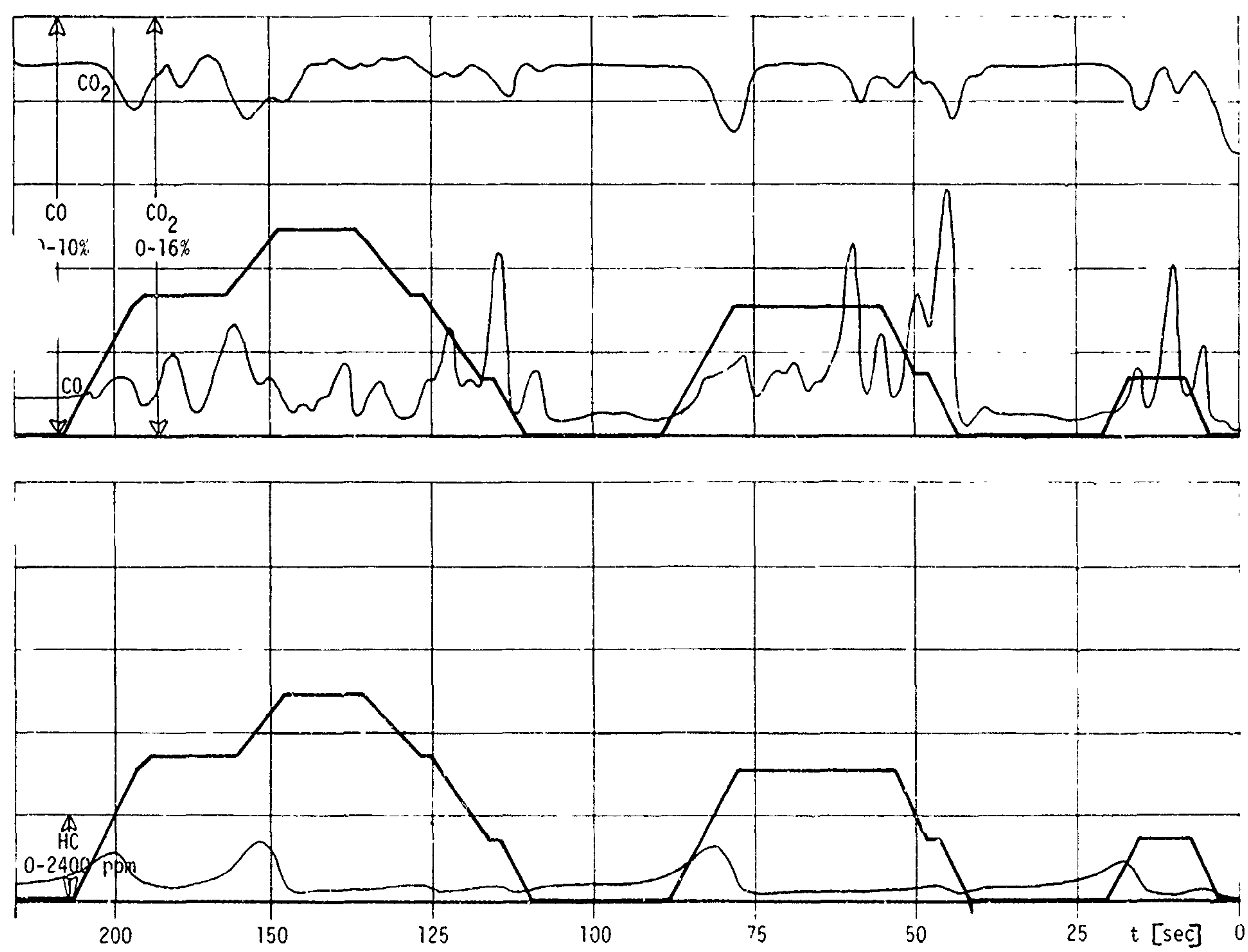


Fig. 8 - Warm ECE 15 test results on Alfaromeo Alfasud fitted with PCU.

DISCUSSION

R.De Hoff, US

(1) What type of signal compensation was used to form the actuator commands from the oxygen sensor signals?

(2) Do you think that more complex sensor compensation/regulation forms can improve emission performance during transients?

Author's Reply

(1) Oxygen sensor signal is looked at as a lean or rich signal – two state – obviously at low temperatures the signal is excluded. The regulation aim is to cross the stoichiometric ratio by means of an increase in correction as long as control is staying in one side. A limit in the ΔP variation rate is provided.

(2) Yes. The transient operation is very often characterised by low temperatures in the sensor – a limited mapping of the engine which takes into account rpm variation rate and throttle positioning is actually implemented. We consider anyway that for the specific system developed, more sophistication, if desirable, must not impair the simplicity and the large applicability which has been obtained.

Let me point out that for three stock cars the same computer board with only an on-board dip switch adapation is capable of satisfying ECE 15 emission requirements.

A UNIFIED DIGITAL APPROACH TO THE CONTROL OF A DIVERSE RANGE OF ENGINES

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SUMMARY

The object of the paper is to review the trends in gas turbine engine control systems and to show the work that is underway to meet future demands.

The emphasis is on digital systems, and because of this the point is immediately apparent that there is a definable pattern between diverse applications. Thus there is a degree of commonality in both the hardware and software for controls for helicopters, civil transport engines, industrial gas turbines and at the top of the complexity spectrum the control for advanced Military power plant.

The theme of the paper concerns this generality, and its achievement with examples from different applications. From the results of this present work some ideas are then put forward on the next stage and the problems and opportunities that are likely to be met.

INTRODUCTION

Engine control systems currently in production are in the main either hydromechanical with some limited authority analogue trimming device, or full authority analogue controls. In the first category are controls on such engines as the Rolls Royce Spey and RB.211, while those with full-authority dual lane electronics include the Olympus 593 and the RB.199. In the helicopter, industrial and marine field the same pattern emerges, though here the approach is to have some form of simple hydromechanical reversionary control instead of dual lane electronics.

In general the control system for each application civil, industrial, helicopter, military is different, and there is very little commonality of hardware. Obviously there is a different emphasis on the requirements, and special problems in each area. Thus the helicopter has rotor governing with its complex response requirements, the industrial control has sequencing and a larger display requirement, the civil engine has thrust rating and the requirement for good efficiency and long life; the military engine has higher complexity with reheat and some variable geometry. Similarly the fuel flow requirements from the simple APU to the full Concorde type system are different and so different pumping, interface and distribution systems are necessary.

CONTROL CONFIGURATION

A set of alternatives for a main engine gas turbine control system is shown in block form on Figure 1. The lower part of the diagram shows that irrespective of the final system there are elements which are common to all. Thus in simplified terms there is a pump package which comprises a backing pump, main pump, relief valve, sometimes an integral filter, and perhaps a speed probe, or an alternator to drive the control electronics.

The next package consists of a main throttle or variable metering orifice (VMO) to control the fuel flow with a pressure drop mechanism operating a spill valve to spill excess fuel back to pump inlet. This VMO can be operated directly or by a servo. It is this item which can take on a variety of forms: hydromechanical, pneumatic, electronic or selective combinations.

From the main throttle valve flow passes to the shut off valve and hence to the sprayer distribution system. In certain cases separate overspeed or overtemperature limiters are provided either operating on the shut-off valve or through some separate spilling device.

All the elements in the main fuel line are functions of engine size since they are dependent upon fuel flow. The control or computer elements - whether hydromechanical or electronic are independent of the flow metering and are a function only of the engine input signals, pilots lever and the control algorithms i.e. acceleration, deceleration range governing etc.

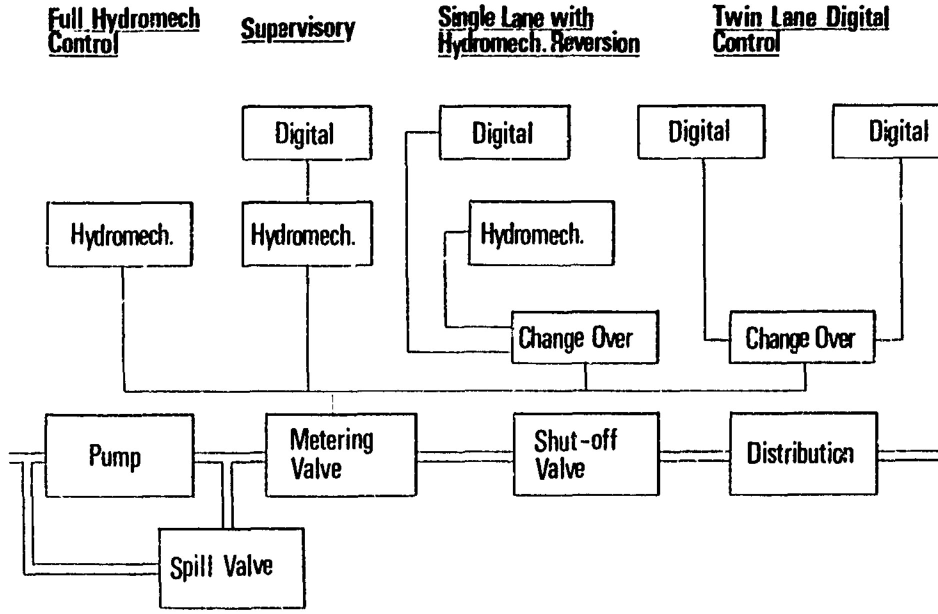


FIG. 1. Alternative Control Configuration

The alternative forms which this Control can take, and which are being considered in various applications are:-

(a) Full hydromechanical

(b) Full hydromechanical with a supervisory electronic trim

(c) Full electronic with a changeover in case of failure to a hydromechanical back up.

(d) Full electronic with a changeover in case of failure to a further electronic unit.

At no point are systems being considered at the moment with only one lane of electronics without manual back up. Similarly there are no systems being considered - as with avionic and fly by wire systems - which are triplicated.

The supervisory control (b) is being considered for civil aircraft and can be looked upon as a halfway house, towards the full electronic systems. Systems (c) and (d) both provide dual redundancy, but the first uses a mechanical back up. The degree and complexity of the back up system depends upon the application, the mission requirements, the number of engines and the complexity of the control problem. One approach is to use the minimum amount of hardware and in the limit the control could consist of a pilot operated tap with perhaps some altitude compensation.

The real choice depends upon a detailed study for each application showing the advantages in terms of weights, cost of ownership, complexity, reliability and above all integrity targets. The reasons for the range of options are partially a measure of the faith which the operator has in the integrity and reliability of the electronics. With a hydromechanical control there are millions of hours flight experience to back up any prediction; with a digital system this experience is lacking.

Further and perhaps more importantly, service returns on hydromechanical units show that less than 5% - 10% of all confirmed defects result in flame out or engine shut down. In general the type of faults occurring with hydromechanical units are mainly as a result of some wear which occurs at a slow rate. The early results of this wear are changes in calibration, perhaps hysteresis. Because the process is gradual it can be sensed by its effect on the engine and the chances of any degradation in control causing engine damage are slight.

With electronic controls this is not so, and except in special cases there is no equivalent "graceful degradation". Thus either the electronic control must be 10 times more reliable than the equivalent hydromechanical unit (to achieve the same in flight shut down) or dual redundancy must be used.

Hence the range of options. Considering however, the digital control unit in the different configurations, it can be shown that these are remarkably similar.

DIGITAL CONTROLLER

Structure

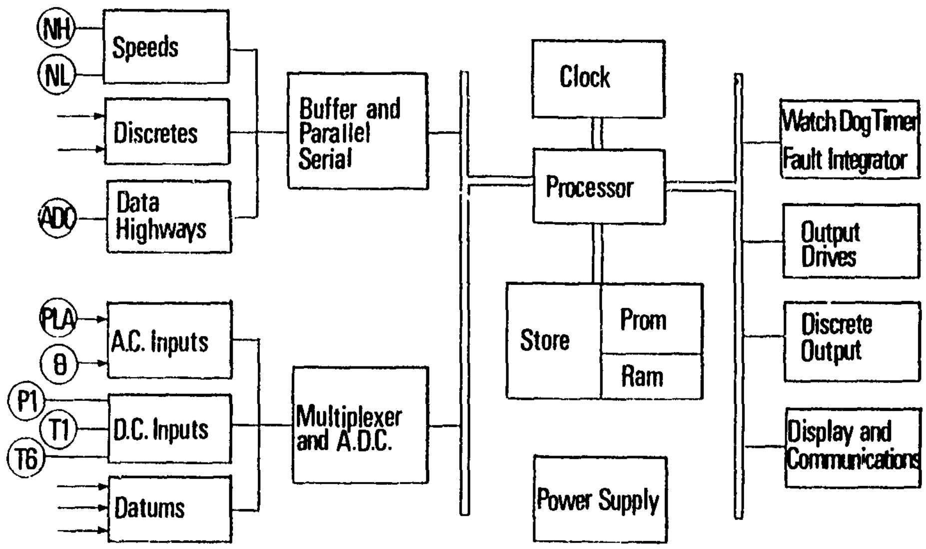


FIG. 2 Digital Control Structure

In simple terms the role of the digital controller in the above applications is to take in a set of input signals,to convert them into digital form and to condition them viz filtering and isolation, to process them according to processor predefined program instructions and to output the results in the manner required. The methods used to input and output the data are standard for any application. The system is "customised" to its final application by means of specific inputs and outputs and the specific program instructions.

A simplified diagram of a typical microprocessor control is shown on Figure 2. On the left hand side are the inputs and on the right hand side the outputs. The central portion of the diagram shows the processor with its interface to the input/output highway and its connection to the memory. The memory highway is a high speed parallel bidirectional highway but because of the reduced throughput the I/O highway may be serial (cabling requirements can thus be reduced from over 19 wires to 8 or less).

The memory consists of two areas: one, programmable read only memory for the control program and read only memory for storage of temporary results. A specific area of the PROM is usually dedicated to constants, datums, gains which,cater for some future change with minimum disruption to the memory.

Attached to the processor is a crystal controlled clock which provides a reference timing or frequency source and is divided down to provide reference signals for speed measuring circuits and the sample rate interrupt.

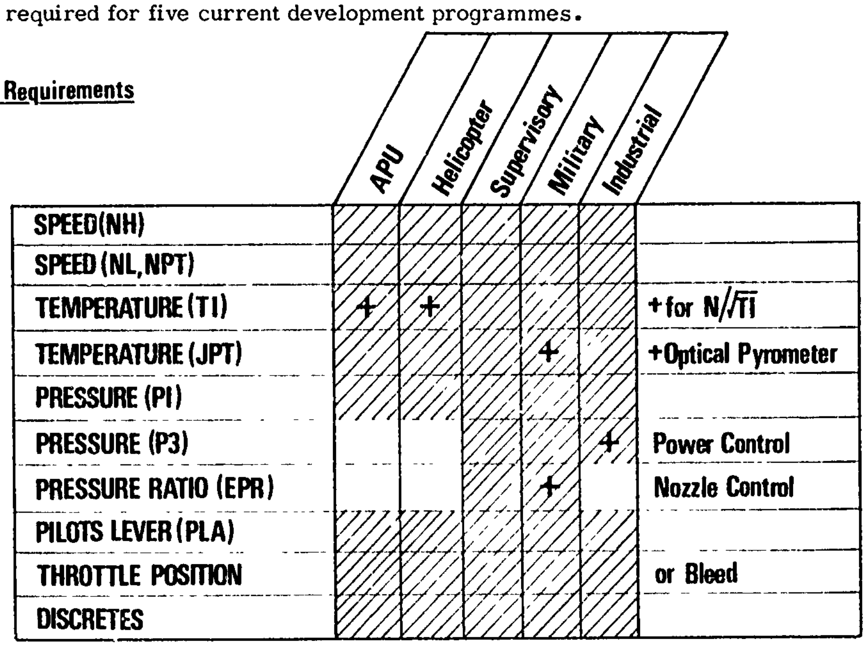
The other item is the power module. Standardisation is possible here since it is required to take in standard aircraft power supplies and produce regulated voltages, typically 5v, ± 15v and 28v to power the circuits within the unit. In applications to date, the use of a dedicated generator has presented little problem, since these have been supplied with their own rectifier/regulator units producing a nominal 28v dc.

Input - Output Signals

The structure above has been discussed without reference to application and it can be seen the hardware composition can be the same for say a supervisory trimming control or a helicopter or a dry engine single lane control. The amount of store will depend on the application but even here store is available in blocks and in general store requirements are similar. Hence a module containing the processor, the store and clock, would have a common use.

Consider now the input requirements for the different applications. Figure 3 shows the parameters required for five current development programmes.

FIG. 3 Input Requirements



By having modules for each input and each output a standard "pack of cards" can be created from which a selection can be made for any application. The cards will then interface to the processor and store modules above.

Self Monitoring and Testing

It has been a general experience that as aircraft have become more sophisticated, and the numbers of electronic systems installed have multiplied, so the ratio between maintenance and flying hours has increased. This trend has been particularly marked in engine control systems, where in recent years we have seen the introduction of complex electronic systems into the most demanding environment on the aircraft, and into the area of responsibility of maintenance personnel whose experience is predominantly mechanical. When these factors are applied to systems with somewhat limited test facilities, the result is a predictably high removal rate and a lot of unnecessary maintenance actions.

Digital systems offer the best solution to these problems, in that it is relatively easy to provide effective built-in-test equipment (BITE) with minimal additional hardware. A number of engine control systems will be discussed in the following pages, and all of them have BITE capability based upon the use of the control computer. The only real variation between the systems lies in the hardware approach to checking that the computer system is functional.

Given that the control computer is fully operational within the system, then it can be used to check out other components within the control loop. The input signal conditioning circuits are amenable to credibility checks, of which three are particularly easy to apply, namely:-

(a) The input signal is measured and compared with predetermined limiting values

(b) Input signals are sampled at fixed intervals so that the difference between successive values can be compared each sample period with stored maximum rate of change values.

(c) The computer may carry a model of the engine and fuel control.

Outputs from the electronic controller are most readily checked by feedback techniques. Typical examples are listed below:-

(a) Electrically actuated position servo - position signal fed back to suitable input channel. The actuator loop can then be exercised during ground check.

(b) Torque motor drive - torque motor current signal fed back to input channel, allowing direct input/output comparison.

(c) Discrete output - additional output switch driven from same source is fed back to discrete input channel.

Power supplies within a control system are regulated, and can be monitored using one or more analogue to digital converter input channels. The measured power supply voltages are compared with preset numbers stored in the computer memory.

These tests provide an excellent basis for detecting faults both within the electronic control unit and within each control loop. They all depend however on effective computer monitoring, which is based upon hardware and software checks. Software checks are of three main types:-

(a) Instruction check - the computer executes a program designed to exercise the full range of instructions used by the control. The known result of this computation is checked by comparison with a stored word in the computer memory.

(b) ROM sumcheck - the control program and its associated constants and tables are stored in fixed read - only memory. If the computer adds up all the numbers in the ROM a known invariant answer should result.

(c) RAM check - the scratch pad memory is checked by a program, writing 1's and 0's to each location in turn.

Hardware checking is frequently carried out by using a watchdog timer. Normal computer operations are timed by means of a crystal controlled clock. Operation of the watchdog timer is shown in the simplified timing diagram of Fig. 4. The sample rate clock interrupt occurs at fixed intervals. At a preset time after the SRC interrupt, the Watchdog timer generates a window of known short duration, during which time the computer must output to it a safety word, which has been computed using the software checking procedures outlined above. This safety word is compared with a hard-wired number built into the watchdog timer, and unless the computer has produced the correct result at the right time, then the monitoring device inhibits the action of the controller in a suitable fashion. The timer is usually combined with another device, the fault integrator, to prevent excessive interruption of normal control. The fault integrator counts sample periods with and without faults, and if the ratio of bad to good cycles exceeds a preset number then it either latches the control into a freeze mode or shuts it down, depending upon the system and plant safety requirements.

If the computer responds correctly to the watchdog timer, then the control cycle continues as shown in Fig. 4. Firstly the output values computed in the previous sample period are sent out to the various actuators and output peripherals, then new input values are read in, checked, and used in the control and safety calculations. The cycle then repeats itself.

The monitored digital computer is thus capable of providing comprehensive built-in test facilities in a system with the addition of minimum hardware. If fault codes are allocated to each checking procedure during software design, then the computer can be used to locate and log in a dedicated non-volatile memory any faults that have occurred during a period of operation. It then becomes standard procedure to read out the fault codes if any malfunction is suspected, and also at regular maintenance periods.

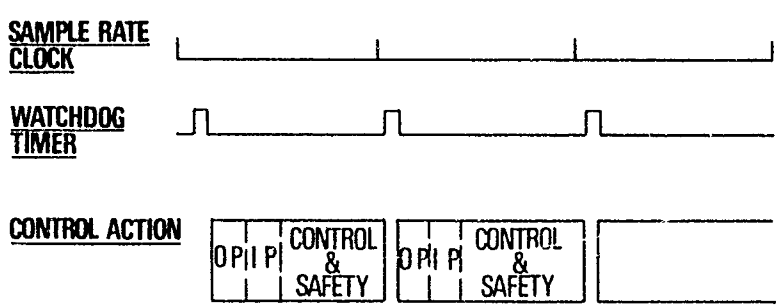


FIG. 4 System Timing Diagram

SOFTWARE

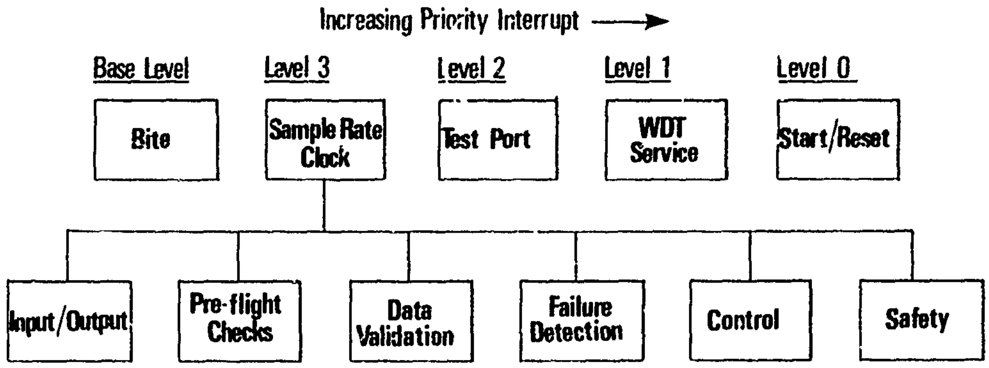


FIG. 5 Hierarchy Chart

Experience on different applications with a range of microprocessors (Intersil IM6100, Texas SBP 9900, Ferranti F100L, Motorola 6802), has shown the need for software standards which have to be rigorously applied. The standards refer to documentation, traceability and change control. The best approach has been to follow the equivalent hardware principles.

Software is designed on a hierarchical, modular basis. The total software task is decomposed into a number of functionally free-standing software modules ranging from those at the highest level defining system strategy, such as interrupt handlers, to the basic arithmetic and logical building blocks. Fig. 5 shows a typical software hierarchy chart which is drawn up at the beginning of the design process. It will be noticed the actual 'control' part of the hierarchy is only one part and that safety, data validitation, ground test interrupt structure are as relevant - and these are common across a number of applications.

BLOCK	MNEMONIC AND SYMBOL	PARAMETERS
B 1 Subtract	SUB I/P1 + ; I/P2 − ; O/P	SUB Input 1 Input 2 Output
B 2 Adder	ADD I/P1 + ; I/P2 + ; O/P	ADD Input 1 Input 2 Output
B 3 Multiplier	MULT Multiplier I/P ; O/P	MULT Multiplier Input Output
B 4 Multi I/O	MOMULT Multiplier I/P1 ; I/Pn ; O/P1 ; O/Pn	MOMULT Multiplier Input 1 , , Input n 0000 Input 1 , , Output n
B 5 Divider	DIV Divider I/P ; O/P	DIV Divider Input Output
B 6 Function Generator 2D	FUG2D I/P ; O/P	FUG2D Input No of points Address of y's Output
B 7 Variable Function Generator 2D	VFUG2D I/P ; O/P	VFUG2D Input Address of x's, y's Output

FIG. 6 Software Modules

Because control engineers have been trained on simulation with analogue type control diagrams we have developed our own control language which is independent of the computer and its associated assembly language. It is based on our Simulation language developed in 1969 (Ref. 3) and has a number of definable functional blocks (viz adders, integrators, lead/lag networks, logic) See Fig. 6. The control engineer 'describes' his system from his control diagram with the appropriate blocks, lists them and passes them through a diagnostic and check computer program. The pain of 'debugging' thousands of assembly programme statements has therefore been eliminated. This process is applied to each block in the hierarchy chart.

A small software team maintains the library modules and generates the necessary software support documentation. These include retrieval utilities, change programs and acceptance tests.

The advantages of the approach are: logical sub-division of the task, early integration, independent testing, reliance on key personnel avoided, visibility and use of standard proven modules.

APPLICATIONS

Objective

The object in the next section is to show how the widely different applications and requirements outlined in the early part of the paper can still be met with the generalised hardware and software described under the digital controller. The emphasis will be on some of the special features of each system and not on the basic digital hardware and software.

HELICOPTER

The helicopter control has to be low cost yet have high integrity and still meet the sophisticated transient requirements of rotor governing. The system presently under development for the US Army ATDE programme consists of two engine mounted units.

(1) A fuel metering package containing backing pump, filter and main fuel pump, fuel metering valving, for both automatic and manual control modes, and an Inlet Guide Vane actuator, together with a dedicated alternator.

(2) A single lane, full authority digital electronic controller providing compressor and free-turbine speed governing, proper control of engine transients and transmission torque management.

The control uses the "Slave Datum Principle" shown in elementary form on Fig. 7.

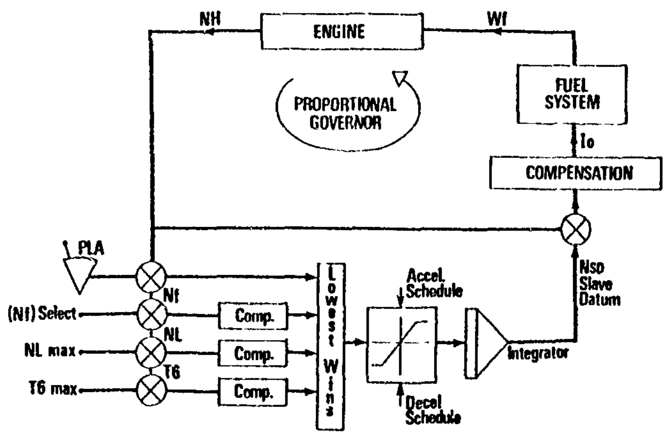


FIG. 7

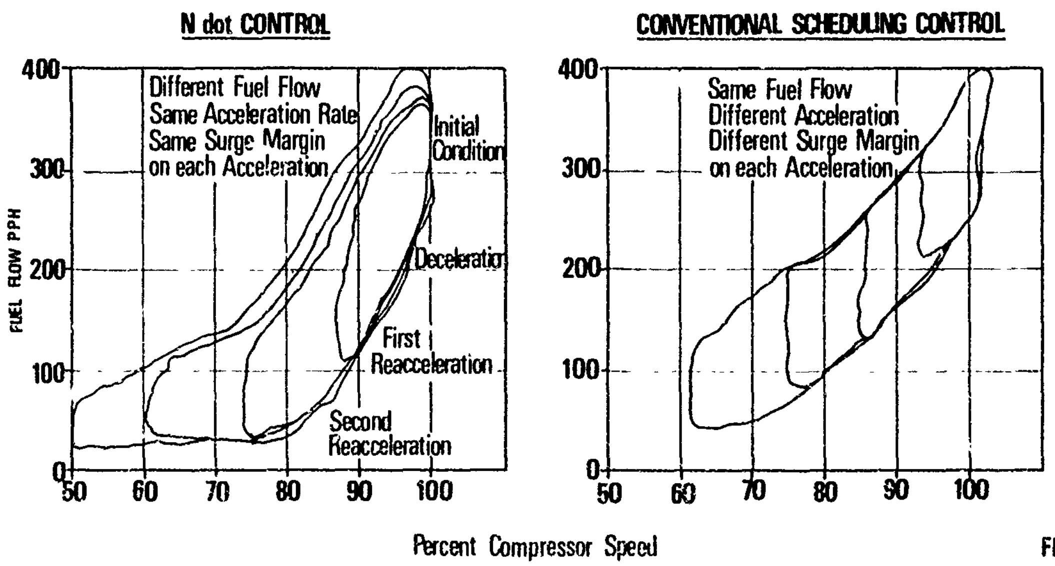


FIG. 8

The datum for the proportional governor, instead of being simply the required engine speed, is a "Slave Datum" derived from the integrating branch of the control.

Governing and limiting functions are achieved by generating error signals for the relevant engine parameters (e.g. shaft speed(s), turbine temperature, transmission torque etc.) and comparing them on a lowest wins basis. The least positive, or most negative, error passes via a limiter to the integrator, the output from which is the slave datum for the proportional governor. The presence of this integrator ensures accurate, truly isochronous governing.

Acceleration and deceleration control is achieved by limiting the positive and negative extent of the input to the integrator. The resulting control is closed loop on dN/dt ("N-dot") and operates in the proportional mode.

The high closed-loop content of the control, which also extends into the starting regime, leads to a simplified fuel metering requirement. The resulting control performance is relatively independent of fuel metering calibration, permitting the use of a very simple interface and giving a high degree of insensitivity to wear and the effects of fuel contamination.

Other features of this control configuration include: its reliance , predominantly, on shaft speed which may be measured accurately with high reliability and low cost, as the control parameter; the use of reset mode power turbine governing, found to be advantageous in helicopter applications; the ability to handle multiple governing and limiting requirements with a minimum of complexity and without any "take-over" problems.

Of interest is the acceleration control and its effect on "Wave off's" or reslams (A wave off is the manoeuvre where an engine having stabilised at high power is suddenly decelerated and then immediately reaccelerated). A series of such manoeuvres is shown on Fig. 8. The N-dot control provides just sufficient fuel to maintain the scheduled acceleration rate. Hence, during wave-off conditions, the overfuelling is substantially reduced to maintain the same scheduled acceleration. This reduction in overfuelling eliminates the high temperature and lower surge margin frequently experienced with more traditional flow-scheduling controls.

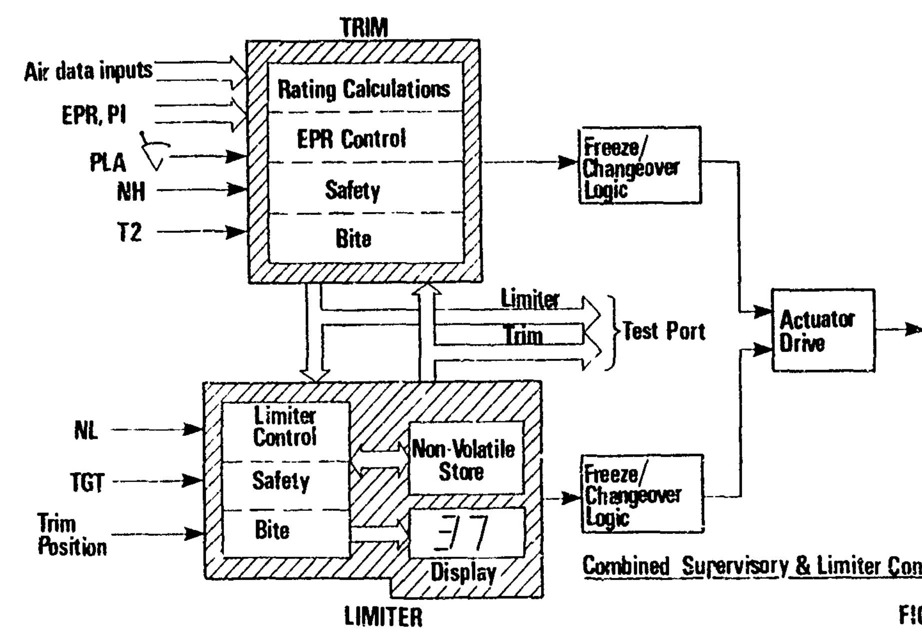
Rotor governing and the matching of the starboard and port engine presents special problems. The dynamic characteristics of a typical rotor system is complex and recovery by one engine after failure of the other is an example where rotor governing and gas generator control performance is at a premium.

SUPERVISORY

The Supervisory Control is designed principally for application to large turbofan engines in civil aircraft. A full function hydromechanical control is fitted to the engine, and the electronic control is used to provide accurate flat-rating, limiting and built-in-test. Fig. 9 shows the main features of the control, which consists of two electrically separate sections for the trim and limiting functions, each having its own power supplies and microcomputer.

The main function of the trim is to control engine EPR, which is measured by vibrating cylinder pressure transducers and transmitted to the control via an ARINC 429 serial highway. Air data inputs are available on a second ARINC 429 highway, and these parameters together with the signals from dedicated transducers are used in the rating and control calculations.

The limiter control normally drives the fuel control actuator and receives inputs from the engine (NL and TGT), which are used for limiting, and the trim control output. Thus if the control is functioning correctly the trim carries out its control calculations and then sends a signal in serial digital form to the limiter which trims the engine fuel accordingly. Correspondingly the limiter sends parameters such as NL and trim position to the trim control. The trim - limiter data links are also connected to the control unit test port , so that a wide range of tests can be carried out at a second - line maintenance facility with appropriate test equipment.



Combined Supervisory & Limiter Control

FIG. 9

Notable features of the trim control are that the rating control calculations are carried out over four EPR control cycles, safety is based upon a computer/watchdog timer combination as previously described and the BITE facility includes a fuel system model which is used firstly to minimise control parameter overshoots when the electronic unit takes over control from the hydromechanical system, and secondly for fuel system condition monitoring.

The limiter primarily prevents engine NL and TGT from exceeding preset limits. In addition however it has a non-volatile read/write memory which is used to store fault codes, and a fault display. When installed on the engine the unit will log up any faults detected during operation, and these may be read out as numbers on the display at a convenient time. The fault codes are remembered even when the unit is depowered. This facility is a most powerful maintenance aid which is particularly useful for locating intermittent faults.

ADVANCED MILITARY

The type of control described here is suitable for a reheated military engine and its future derivatives, or with the deletion of the reheat lane a complex non-reheated engine. Fig. 10 shows the overall electronic system configuration. The dry engine control comprises two identical lanes, either of which can be selected by the pilot. A single lane of reheat is provided. The only areas of duplication in this latter part of the control are the emergency shut down logic and nozzle close and reheat cancel actuators.

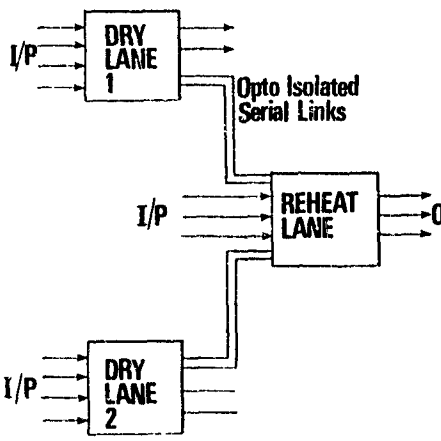


FIG. 10 Reheat Configuration

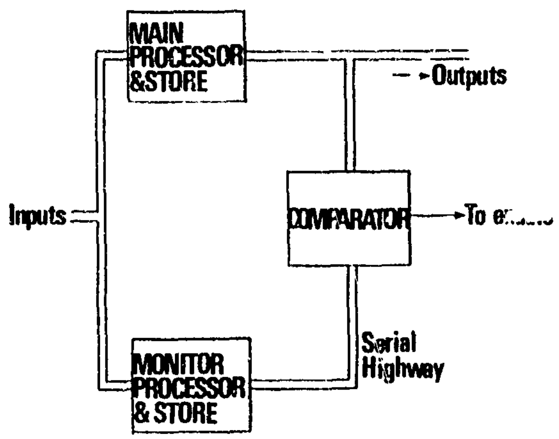


FIG. 11 High Integrity Computor

The Advanced Military Control uses standardised input/output circuitry in common with the other controls described in this paper, but has one unusual feature. This is the high-integrity computer which is shown schematically in Fig. 11. This consists, as shown, of two micro processor based computers driven by a common clock. Only the control computer can send command signals to the output drives. Both receive identical information via serial input highways, and execute identical programs. Outputs from both computers are compared on a bit-by-bit basis, and only if the outputs are identical to this level can the output drives be enabled. This approach provides essentially 100% monitoring of the control computer function.

The output from the comparator is fed to a block of circuitry comprising a watchdog timer, fault integrator and initialisation logic. If a fault condition is indicated then a typical response would be:- Freeze actuators, Initialise Computers, Return to normal operation if no further faults occur. If fault condition persists, the fault integrator will initiate lane change (dry engine) or freeze and/or shut down (reheat).

Thus the Advanced Military control is designed to depend upon its self-monitoring capability. This is essentially because it has been conceived from the beginning as a full-authority control with similar redundancy, and must meet stringent integrity targets. Generally speaking the requirements for dry engine control are more difficult to meet in practice. For example, whereas for a dry engine the probability of a failure leading to reduction or loss of thrust is typically defined as 3 X 10^{-6} per hour, the corresponding figure for failures leading to reheat extinction is 3 X 10^{-4} per hour. Clearly this allows a different approach to configuring the reheat controller as noted in Fig. 10 above.

The reheat control has its own dedicated transducers for parameters not available from the dry engine control lanes. Inputs already available on the dry engine control are transmitted in serial digital form to the reheat control, thus providing these signals more reliably than a set of simplex dedicated transducers.

Industrial Control

In addition to the usual gas turbine controls for governing, temperature control power control etc. there are sequence requirements and associated with both a large display requirement.

Sequence controls in this context are defined as "the outputting of signals to equipment in a pre-determined sequential order according to the condition of associated equipment". The process therefore involves monitoring the associated plant condition, performing various timing and logical functions and outputting the appropriate commands. In addition it is also necessary to display the current sequence state and/or the reason why the sequence is stopped or curtailed in the case of a fault condition.

A typical sequence would provide for say: start interlocks, manual start and run up, lubricating oil pump sequence, fuel pump start sequence, starter motor control sequence, synchronising sequence, loading sequence, shut down sequence.

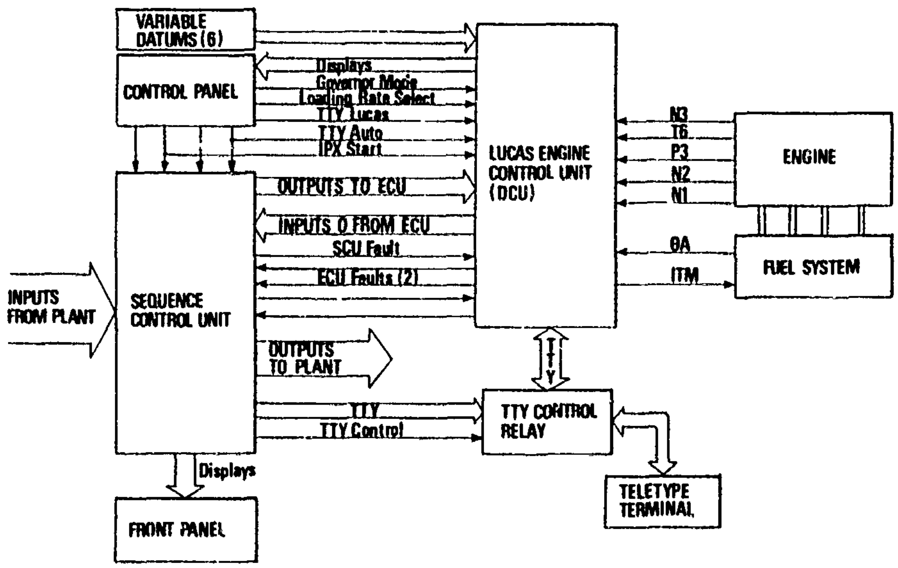


FIG. 12 Industrial Sequence & Main Control

In general sequence controls are dependent on the application and each with different specifications. Because of the variability the digital Modular approach shows advantages. Fig. 11 shows a typical arrangement in which one processor is dedicated to the control functions and the other to the sequencing. This has the advantage that sequence changes can be incorporated without any risk of affecting engine control performance. The interface between the two processors is via the I/O highway.

THE HYDROMECHANICAL ELEMENTS

The emphasis so far has been on the electronic aspect of controls but the hydromechanical side should not be dismissed. Obviously even with the most 'electronic solution' there will be need for pumps, interfaces, accurate transducers, shut off valves and distribution systems which may be increased with additional valvery to cater for phased or sector burning. With the less electronic solution - the supervisory or manual back up control this need will be increased.

The progress on the hydromechanical elements has been less glamorous but still steady and purposeful. On fuel pumps steady progress has been made to accept higher temperature fuel (up to 180°C), to have longer life (above 16000 hours), to run with greater tolerance with dirty fuel, and to operate with higher efficiency and so reduced fuel pumping temperature rise. The ability to operate with a wider range of fuels with worse lubricating properties is also being pursued as well as the antimisting kerosene safety fuels.

ASSESSMENT AND FUTURE APPLICATION

In the first AGARD Power Plant Control Symposium held in 1974 a description was given of a complex digital power plant control (Ref. 1) using a powerful mini computer. Since then this unit has flown in the Concorde and a large number of useful lessons have been learnt. In the section on future application in the early paper reference was made to the emergence of the micro processor and the profound effect this would have on controls. In the present AGARD symposium most of the papers deal with these devices.

If we consider the first generation digital engine controls as comprising of the mini computer (say 1969 - 1975) then the second generation must surely be the micro processor (say 1976 - 1985) and it is of interest to ask whether there will be a third generation and how it will be different.

The first generation was successful in laying the foundation for the circuits, the software, the testing and in proving the technical feasibility. It was also successful in changing people's attitude to digital systems and provoking interest. With hindsight, and being critical, it failed in that it never went into production, so that predictions on cost, reliability and maintenance costs were never proved.

The second generation has started with a much wider area of application, and with the advantages of reduced cost and higher reliability components. Every attempt has been to modularise and to reduce cost. The hydromechanical interfaces and transducers have been more fully researched. The second generation should be successful with we hope few problems.

To look at the third generation when the second hasn't yet achieved production service may appear optimistic, but there are two good external pointers to the future. The pointers are the need to conserve fuel, and the predicted advances in the semi conductor industry with the growth of VLSI (very large scale integration with 100-20,000 circuits per chip), and perhaps more importantly, the increasing use and sophistication of the micro processor in the automobile industry.

The latter will result in reduced cost special purpose chips and a "Control system on a chip" with multiple redundancy may be possible. The concept of one piece of hardware for any application becomes more a reality where all possible inputs are arranged for and only the selected number for the application used.

The software will be equally important with more emphasis on adaptive solutions and less settings, datums and slopes required. There will be better communication with the pilot or the management computer, and more attempts made to optimise the control algorithms with perhaps additional engine health functions. The hydromechanical systems will be simpler and the transducers more accurate and reliable.

CONCLUSIONS

The paper has attempted to show how the control industry is getting nearer to the concept of a general purpose control and how common modules can cover a range of applications both in hardware and software. In confirming this theme examples from different applications have been shown and some prediction made for the future.

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ACKNOWLEDGEMENTS

The authors are indebted to the Directors of Lucas Aerospace Limited for permission to publish this paper. They wish to acknowledge the support of their colleagues in the Lucas Organisation and the co-operation of the Ministry of Defence (Procurement Executive) and Rolls Royce Limited.

DISCUSSION

V.Amoia, It

First of all, thank you for your excellent presentation. I am not asking a question, but just a comment: As far as reliability is considered, would you please comment on the use of fault tolerant architecture.

Author's Reply

We make extensive use of standard software validation techniques to check input and output signals. Computer checking includes software sumchecks and instruction check programs.

Hardware checking is particularly based on the use of the computer to monitor the rest of the system, thus special to purpose hardware is only required to show that the computer is working satisfactorily. The level of this monitoring depends on an application and particularly on reliability targets. For a system with demonstrably safe failure modes, as with the use of limited authority, a watchdog timer and fault integrator is quite adequate. For a full-authority duplicated control, or even a simplex one in the case of reheat, the detection of computer faults becomes more important still, and is best accomplished by using a similar computer operating synchronously with the control computer. In this case a simple, reliable comparator provides the required failure detection means.

ADVANTAGES OF THE DIGITAL TECHNOLOGY FOR THE REALIZATION OF ENGINE CONTROL SYSTEMS

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1. INTRODUCTION

Modern eng nes will be controlled by digital control units. Requirements to be met by the digital technology and the advantages resulting therefrom will be pointed out in this paper.

Most of the fuel control units, generally used nowadays, are hydromechanical ones. They are especially characterized by their high rigidity and reliability.
However, due to limitations of weight and volume, it is nearly impossible to realize in this technology complex control laws. The introduction of electronical control units by which these control functions can be realized was made possible by the operational amplifiers on an analogue basis. In addition, by this it was possible to increase the requirements to be met by the engine. The introduction of the digital technology promises further improvements such as shorter engine acceleration, a better and easier adjustment of the control rules to individual engines, integrated engine/flight control and exact realization of engine characteristics.

2. STATE OF THE ART

Today most engine control units are still developped and produced on a hydromechanical basis. Often electronical units such as the N1-limit computer of the engine GE-CF6 at the Airbus are superposed on these control units.

There is, however, already a number of electronical control units - mainly analogically realized - where the main fuel system is still designed in a hydromechanical way.
Figure 1 shows the principle structure of such a control unit.
It has to:

- carry out a speed control for the high pressure compressor by means of electronical control of the main fuel system according to throttle position,
- to avoid dangerous modes by limiting rotations, accelerations, and turbine -outlet-temperatures, and
- to control nozzle area and afterburner fuel flow.

Besides, the concept differs from the conventional hydromechanical engine control units only by the additional $\dot{N}_H$-limitation.

From this you can see that in the present electronical control units for multiple spool engines, too, only one spool is controlled. For safety reasons, the electronical basic engine control units are realized in a redundant version(Fig.2) in contrast to the hydromechanical ones (the latter include an emergency system).

In case of a system loss of the electronical control unit the engine-shafts will be monitored by an overspeed governor The overspeed governor is equipped with separate sensors and it limits the fuel supply for the engine.

3. REQUIREMENTS

The requirements to be met by a digital engine control unit for future gas turbines will be defined based on the experience made with analog engine control units. Among the requirements specified by the user the aspect of the engine handling is above all of most importance. For example a fairly linear relationship of the angle of throttle and thrust as well as a stable engine operation in all ratings and in the whole flight range are required.

Further requirements are mainly determined by the engine and the aircraft.
For example dangerous engine operating conditions (pumping, overheating) should be avoided by limitation of relevant engine parameters. The requirements determined by the engine are already considered to a satisfactory degree in present systems. The requirements called for by the user, the aircraft and its equipment will have to be taken into account much more when developping future engine control units. Especially an interaction between engine control and flight guidance system is required. By computing additional data of flight condition and disturbances (e.g. gun firing) an optimum engine handling also during extreme maneuvers as well as an optimum steady engine-state in the whole flight range should be guaranteed. The safety requirements to be met by the engine control unit have an essential influence on the realization requirements with respect to the technical equipment. The probability of loss required for an engine control unit should be less than 10^{-4} per hour. This value can be achieved by a duplex system. Proceeding the assumption that future aircraft will be equipped with two engines and that it is possible to fly the aircraft with one controlled engine only, the total probability of failure is approximately 10^{-8} per hour.

Other requirements to be met by future engine control units relate to the improvement of the testability and maintainability and, in addition, the simplification of the complex adjustment of the control unit.

4. ADVANTAGES OF A DIGITAL ENGINE CONTROL UNIT

Based on some examples it is tried to demonstrate the possibilities and advantages of the digital technics which are specific for the engine control.

4.1 Integrated Engine and Flight Control

An appropriate interface is necessary for the interaction between engine control unit and flight guidance systems. In a digital realization of the engine control unit it is possible to have a coupling with a future aircraft data bus. By means of this coupling it is possible to read in data e.g. from Air-Data-Computer or flight control system as well as to transmit engine data to the engine-life-recorder, flight control system or display system (Fig.3).

4.2 Realization of functions

The representation of characteristics may be rather complex in an analog system if high accuracy is required. For the realization of the function of the maximum cruise limitation line of the fan speed for the CF6-engine (fig.4) seven reference points are necessary for the required accuracy within which a linear interpolation is carried out. The circuit necessary for the characteristics will be realized on one IC-board.

In a digital engine control unit it is relatively easy to represent functions with high accuracy. The above mentioned engine characteristic is realized in digital technic in the N1-limit-computer of the Airbus A300.

The complexity of this realization is comparatively small.
There are two possibilities:

a) Two data are to be stored for each reference point. A linear interpolation is carried out within these points. (Sub-program with 30 statements);

b) the curve is represented by a function of n-th degree. In this example, n = 5 (6 constants, 10 statements).

In general it can be observed that with a minimal supplementary effort any accuracy may be achieved by the digital solutions. The results of a digital calculation can be reproduced. The characteristics can be adjusted by reprogramming with respect to the actual engine mode. In contrast to this in an analog realization the accuracy can be lessened e.g. by a temperature dependent drifting.

4.3 Reliability

By means of software procedures it is possible to detect sensor failures and defects occuring in the hardware of a digital control unit. This effect can be used for the development of a failure self detecting engine control unit.

4.3.1 Failure-self-detection by Software

It is possible to detect failures in the hardware of the control unit, i.e. in the CPU, memory and interface by means of special built-in test programs. They are processed on-line in the intervalls available during the computing cycles of the control unit.

For this it is necessary to monitor the failure-self-detection separately in a supervisor as the CPU in which the test programs are executed can only detect failures as long as it is functionally in order (fig. 5).

To realize this, the CPU has to reset at certain intervals a timing circuit designed as watch-dog-timer in the supervisor; otherwise the supervisor reacts as in the case of a control unit failure and generates a switching signal.

By supervising the engine control system with a watch-dog-timer and software procedures to test CPU, memory and standard interface it is possible to have a failure-detection rate of 95 percent.

4.3.2 Estimation procedure for the Sensor Monitoring (analytic redundancy)

It is possible to monitor the sensors and the analog input interface by means of estimation procedures for the sensor values. For example to estimate the speed of the high-pressure compressor of a multiple spool engine it is taken advantage of the fact that there is a definite correlation between corrected fuel flow and compressor speeds for a healthy engine (fig.6).

This corrected speed is determined by a simple stationary engine model using besides other parameters the measured fuel flow. In addition, the engine dynamics is simulated in a simplified way by a variable lag type filter and is taken into account.

A monitor/voter is fed by the estimated value $\hat{N}_H$ and the signals transmitted by the N_H sensors. The monitor/voter is able -if necessary- to carry out a majority decision for the localization and elimination of a failed N_H-sensor.

For the acceleration or deceleration of the engine the estimation error is less than 1 percent if the engine dynamics is taken into account by a variable lag type filter. Otherwise estimation errors of approximately 5 percent would occur (fig.7).

In a steady engine state estimation errors should not occur, otherwise they are caused by design tolerances and aging of the engine. However, it is possible to eliminate these errors by exactly adapting the control unit to the engine.

The estimation procedure can be used for the localization of a sensor failure. On the other hand, if both sensor values are within the defined monitor threshold limit and the software sensor determined by estimation differs considerably from the consolidated measuring value, it is possible to conclude that there is a failure in the analog output interface, main fuel system, or engine.

Other engine sensors such as speed of low-pressure compressor, temperatures, pressures can be determined with N_H and $\dot{N}_H$ in an appropriate estimation and calculation procedure. The monitoring is made in accordance with the procedure previously described for N_H.

To sum up it can be said that it is possible to detect and localize failures in the control unit including the analog interface as well as in the sensors by means of the software procedures described for the failure-self-detection and state estimation. And on certain conditions it is possible to assume failures being present in the main fuel system or in the engine. One of the fundamental advantages offered by the procedures described for the failure-self-detection is seen in the fact that they can also be used for preflight tests or maintenance work. This multiple use of this system internal intelligence results in an improvement of testability and maintainability of the control unit.

4.4 Adjustment of Control Unit

Various engine characteristics are mapped in the control unit and design tolerances in the engine affect the control unit quality. Therefore engine control units have to be carefully adjusted to the corresponding engine. For a multi-shaft engine for example, up to 50 values have to be manually adjusted by screws or potentiometers.

In a digital engine control unit the adjustment of the control values to the individual engine can be made by an engine test run on line via a digital optimization computer which is coupled to the control unit. For this purpose the values concerned are registered in the optimization computer memory to which the engine control unit has a direct access. After transmission of the engine input values to the optimization computer, an automatic parameter adaption for the various characteristics can be made via the appropriate strategies and the characteristics can be reprogrammed. Today this reprogramming is made by establishing new PROM cards (fig.8) which are then exchanged for the old ones in the control unit. Here, on line reprogramming of the control unit emerges by the development of electrically erasable memories for micro processors.

5. FEASABILITY

Tests carried out in recent years showed that there are no fundamental problems for the digital control of a multiple shaft engine.

It has been proved that

- sufficiently exact results can be obtained by a 16-bit fixed point data processor,
- a control unit sampling rate of 25 Hz is sufficient for the speed control and limit cycles for speed, accelerations and temperatures, and

- converters with 12 bit resolution can be used for the analog input/outputs.

In addition, it could be shown that today it is already possible to use generally available micro processors (SBP 9900 of Texas Instruments, Intel 8086) for the engine control consisting of the tasks basic engine control, afterburner control, engine/flight control, and monitoring.

Actually, efforts are made in the whole world concerning the development of high ordered languages (HOL), to be used in control units. (PEARL in Germany, CORAL 66 - England, ADA - future standard in the USA ....). This enables a reduction of the high expenditure made for coding the programs which is still normal for the assembler programming and a increased reliability of the software. In addition, the visibility of programs would be improved. There are still generally accepted procedures to be elaborated for the specification, test, modification and maintenance of the software in order to reduce costs and assure a higher software reliability.

6. SUMMARY

In the present paper it could be shown that with respect to their capacity future digital engine control units have essential advantages (integrated engine-flight control, functions, reliability, adjustment) compared to their hydromechanical and analog electronical predecessors. Digital control units have a higher efficiency but will probably be of the same volume than actual control units, as nowadays more than a half of the space available is needed by the power supply and the analog interface.

A considerable reduction of the interface and its volume will only be possible if the environment of the digital computer is digitalized as well, that means if sensors are provided with a digital pick-up, and if a direct digital control of the actuators and the displays is available.

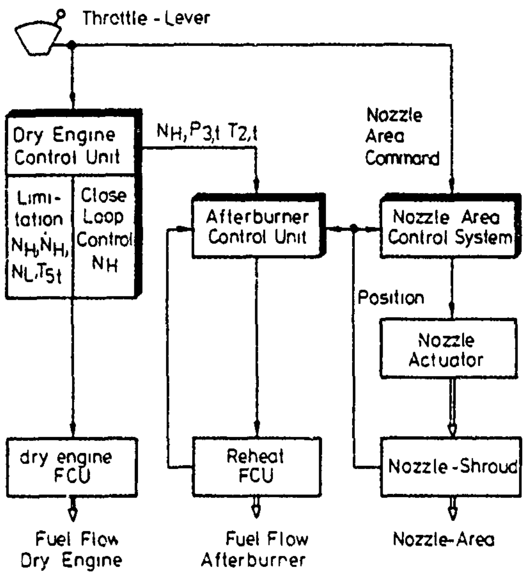

Fig. 1: Structure of an analog engine control unit

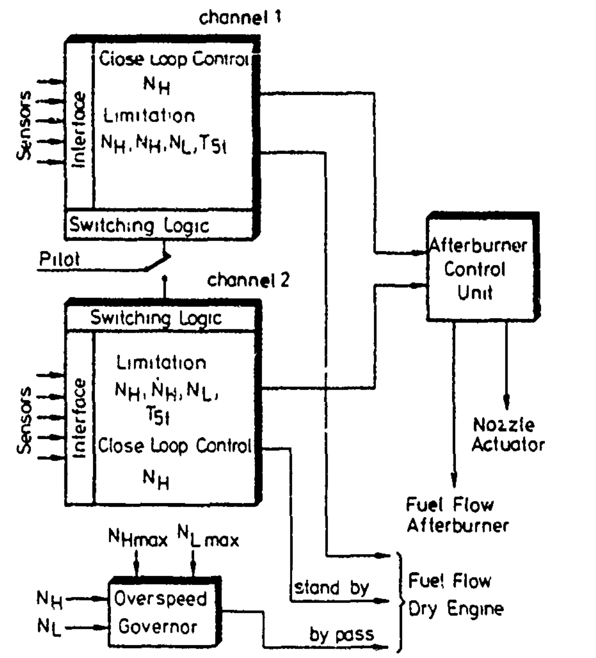

Fig. 2: Concept of a redundant electronical control unit

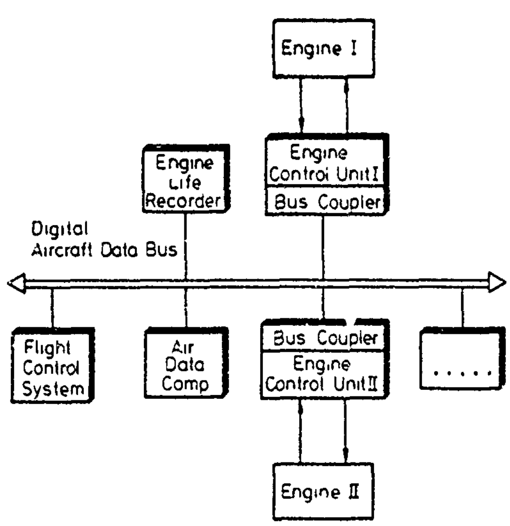

Fig. 3: Communication between the engine control unit and the flight guidance system.

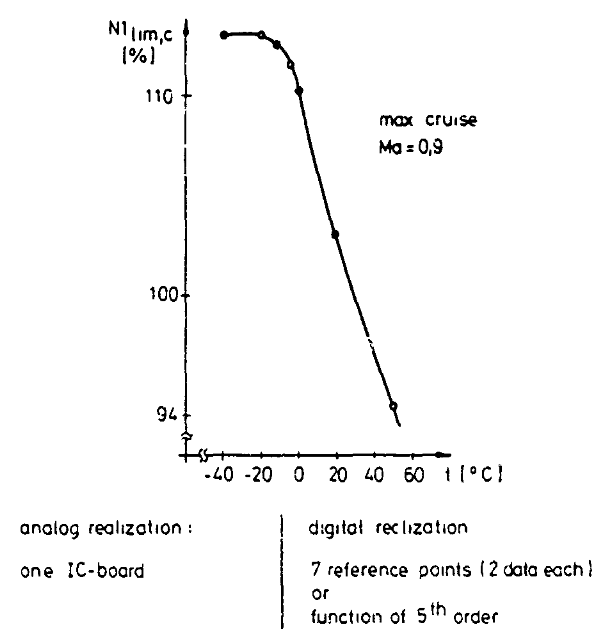

Fig. 4: Realization complexity for characteristics

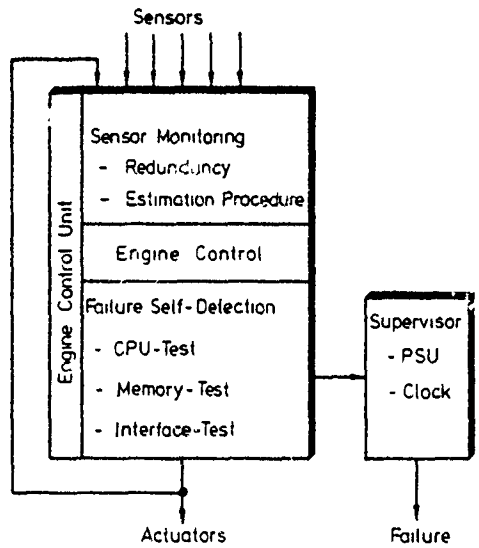

Fig. 5: Failure-self-detection in a digital control unit

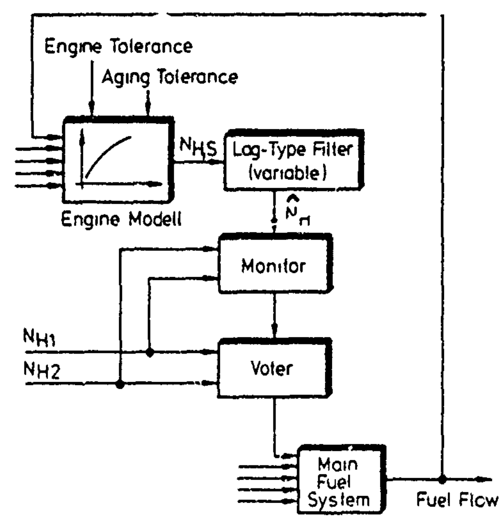

Fig. 6: Monitoring system for the high-pressure compressor speed N_H.

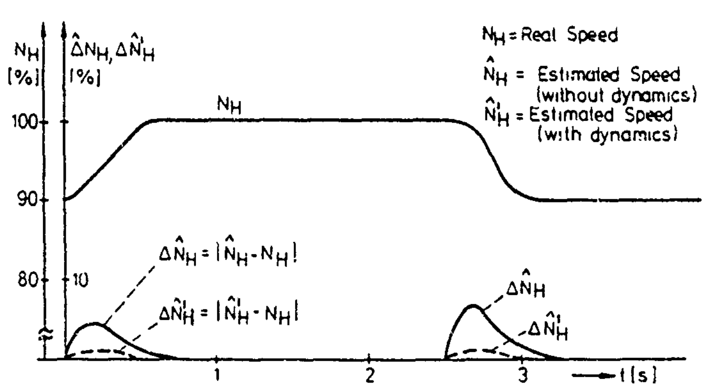

Fig. 7: Estimation of the high pressure compressor speed.

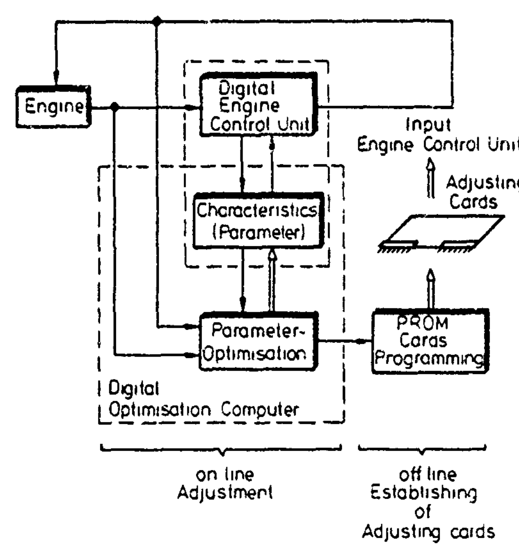

Fig. 8: Automatic control unit adjustment.

DISCUSSION

J.M.Collin, Fr

You say that the use of high level program languages involves reliability and cost reducing factors.

Please comment on reliability of compilers and number of codes in comparison with assembler.

D.J.Hawes, Ca

High Level Languages. Could you please give your opinion of the pass-off in terms of software programming time, traceability, reliability and hardware, between assembly and higher level languages, e.g Pascal.

Author's Reply (to J.M.Collins and D J.Hawes)

We expect that the need of additional storage is less than 40% for the programme-coding.

But furthermore 1 2 k-words are needed for real time monitoring system and runtime software. The software reliability will increase on account of higher visibility of HOL source programs.

E.Roberts, UK

Clarification Is the engine model an on-line model (in the controlling computer) accurate to 1% during transients?

Author's Reply

The engine model is on-line in the controlling computer and it is accurate to 1% during transients for test bed runs

N.A.Justice, UK

Correction to statement. Suffiently exact results can be obtained with 8 bit microprocessors as well as 16 bit microprocessors.

(1) What form of actual hardware do you have?
(2) What type of microprocessor do you use?
(3) Why did you choose that type?

Author's Reply

We have different development projects with different microprocessors.

(16 bit Texas SBP 9900 and Intel 8086:
8 bit Intel 8080/85).

We started our investigations with Intel 8080, the first microprocessor available for flight purposes.

Later on we chose the successor Intel 8085 and on account of accuracy the 16 bit Intel 8086.

For military investigation the SBP 9900 is the only microprocessor with MIL-standard.

T.O'Brien, UK

Your paper states that for a two-engined aeroplane the total probability of failure due to malfunction of the central system is 10^{-8}/hr. Assuming that the failure can be hazardous or catastrophic this probability is totally unacceptable for electronic engine control systems in civil aeroplanes The figure would have to be at least two orders better, i.e. 10^{-10}. Two-engine failures on a twin-engined aeroplane are considered catastrophic and as engine shut down rates from all causes are approximately 10^{-4}/hour it can be seen that the proportion allocated to the electronic control system must be much less.

Author's Reply

The most reliable control unit is unable to improve the reliability of the engine.

We see a verification of a total probability of failure due to malfunction of 10^{-10}/hr only by tripling the systems

R.De Hoff, US

Does the parameter adaptivity procedure suggested require multiple calibration runs of the engine during the life of the engine?

Author's Reply

The calibration work differs from engine to engine, and a parameter adaptation of engine and control unit for the first flight will not be enough

THE DIGITAL CONTROL SYSTEM AS PART OF AN INTEGRATED ACCESSORY FIT FOR FUTURE ENGINES

By: M P Perks and T G Morton,
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Leavesden, Hertfordshire, England.

ABSTRACT

The paper suggests that the traditional approach of designing the control system in isolation from the other accessories on a gas turbine engine may not provide the most cost effective total solution for an engine having a digital control system.

It is considered that the integrity of the digital control can be maintained whilst providing additional functions not associated with its prime control task. This could allow the development of advanced monitoring systems to minimise life cycle costs and achieve maximum aircraft utilisation.

The application of these principles to helicopter engines is discussed and an arrangement proposed which could provide substantial benefits both to the helicopter pilot and to the ground crew. Pilot workload would be substantially reduced by advising him of engine or aircraft management factors on a "need to know" basis. Operators would benefit from regular information on the operational status of the engines.

1. INTRODUCTION

Electrical control of gas turbine engines has been an accomplished fact for over 30 years with control based on digital computers an accepted principle for at least the last 10 of these. Recent demonstrations of the virtues of full authority electrical control are believed to have provided the necessary stimulus for such controls now to be seriously considered for future gas turbine engines in helicopters world-wide. The argument as to whether an analogue or a digital based system would best satisfy the requirements of the particular market is a complex one; it is practically certain however that future military engines will be conceived from the outset as having digital control systems. In the military field the trend is likely to be more and more towards treating the engine as a subsystem in the aircraft, with commands transmitted and reponses received along redundant data highways in the same way as for example, an air data computer. Digital systems generally are the obvious solution for such aircraft.

This paper does not set out to resolve the analogue versus digital question for the helicopter market but is intended to highlight the extended capabilities that a digital control can confer on an engine; these capabilities have obvious benefits in the military field and it is contended that such advantages should be made use of more generally. In defining the advantages, one should start by asking the question "What is the prime function of the helicopter, and what role does the pilot play in the achievement of this objective?" It is clear that the aircraft does not exist to transport the powerplant around and that the pilot has other things to do than look after the engine.

These apparently self evident facts are often overlooked and if taken to their logical conclusion imply that the engine should be a fit and forget component.

It is interesting to note the differences in approach evident in two recent flight test evaluations carried out by a leading U.S. aerospace journal, one of the latest fly-by-wire single engined fighter and the other of a new civil helicopter. The former report hardly mentions the engine at all; the latter contains extensive sections on engine starting, operating limits, gas generator speeds etc. Which approach ought to be the one for the future?

Being realistic, the fit and forget philosophy implies quite a complex engine monitoring system, since it is very unlikely that powerplant reliability could in itself be adequate. If it were then no doubt advantage would be taken to extend life, power etc., and we are back to where we started. Engine health monitoring is again not a new concept and in fact has been an accepted aspect of the operations of large airlines for many years. Of necessity customers in the helicopter market have kept these systems as simple as possible in line with the operational activities of the aircraft. These operational requirements are becoming increasingly complex as the capabilities of new helicopters are exploited. Some operators now utilise limited aircraft management avionic systems to maximise use of the helicopter and reduce the overall cost of ownership, the ready acceptance of the value of such avionics indicating surely that the market is ready for an increasing level of automatic system involvement in the general flight operation of the aircraft.

This paper therefore proposes that digital control should be marketed on a more positive basis such as "It controls the engine, of course, but it also provides additional capabilities which no modern aircraft should be without." It is suggested that the approach most likely to prove attractive to potential aircraft operators is one where there is a significant level of integration of the control with a total engine and aircraft monitoring system. The overall capabilities of one such integrated arrangement are described in this paper and the potential operational advantages surveyed.

2. CONTROL SYSTEM DESIGN

Many possible electronic control systems, both analogue and digital, have been described in technical literature over the last few years, one example being given in reference 1. There is no one "right way" to control a gas turbine engine, many quite different approaches having been adopted to starting schedules, acceleration laws, temperature limiting etc: what may be suitable for one engine may be unsuitable for another. Further, control laws lending themselves readily to a hydromechanical solution may be difficult

to implement within an electrical system and vice versa.

In this paper we are not concerned so much with engine control per se., more with the form of its interface with the rest of the aircraft, and in particular with the pilot. It is in the interface areas where the benefits of digital control as opposed to analogue can become most readily apparent, and where the deficiencies of current hydromechanical arrangements are most marked. There are basically two main interfaces in any aircraft between the pilot and the engine, that resulting from his direct link(s) with the engine control system and that associated with engine monitoring i.e. instrumentation. Both the pilot and the control system currently use essentially the same engine data to perform their respective tasks although additional information may be provided to the pilot for purposes outside the normal scope of the control system, for example, oil system monitoring.

This being so, it would seem reasonable to suggest that if the digital protagonists are right and there is computing power to spare, the digital control could undertake some of the engine monitoring functions itself, thus significantly offloading the pilot. Once this is accepted the whole concept of the man/machine interface may be re-evaluated against a new set of ground rules where, assuming integrity is safeguarded, the main requirement is to make flying the aircraft easier.

3. MAN/MACHINE INTERFACE

3.1 Use of Interface

Any aircraft would require a number of functions to be performed relating to the operation of its power plant and associated systems. These functions may be listed as follows:-

(a) Select the engine operating condition required.

(b) Monitor the health of the engine and its control.

(c) Monitor the use of the engine.

(d) Ensure that engine operation is within cleared limits.

(e) Fly the aircraft to within its cleared limits.

(f) Control the engine directly when necessary.

Performance of each of these functions is affected by the form of the man/machine interface. Traditionally the necessary transfer of information between the pilot and the engine has been achieved by a mechanical link between the pilot and the control system to transmit demands to the engine for normal and direct (reversionary) control, and a display of information on engine operating conditions on standard instruments using electrical signals derived from engine transducers. Fig. 1 illustrates a typical modern helicopter cockpit.

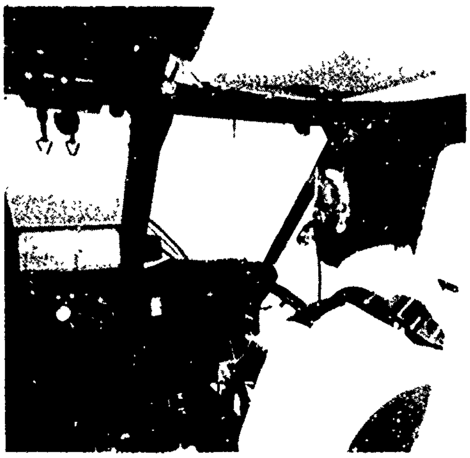

FIGURE 1 - TYPICAL HELICOPTER COCKPIT

A more appropriate electrical version of the "mechanical reins" to meet functions (a) and (f) is discussed below. Arguably, (b), (c) and (d) could be performed automatically provided that the configurations of the systems ensures adequate integrity. These tasks fall into the general category of "control and engine monitoring" and therefore will be examined later in relation to the broader issues of health monitoring as applied to helicopter engines, see para. 4. Aspect (e) is essentially a total aircraft function and therefore involves additional information about specific airframe parameters; to accept this as a candidate for automatic monitoring involves an extension to a total aircraft monitoring approach. Function (f) requires a limited amount of engine performance information but otherwise may be considered as directly influenced by the prime function (a).

3.2 Future Form of Control Interface

The logical consequences of an electrical control approach is that control information between the pilot and the engine should be transferred in the form of electrical signals. To maintain control

integrity a backup path for control demands must also be provided: this could take the form of the traditional mechanical solution but it is considered that an alternative offering adequate integrity together with reduced pilot workload would also be by independent discrete electrical signals. The resultant system has many installational and operational advantages, its main disadvantage being a deep-rooted suspicion in the minds of many people that in the event of a major problem the electrical wire would let them down.

There is no real answer to this except to say that if a whole aircraft can be designed around a fly-by-wire concept then the small step of engine control-by-wire should appear relatively trivial. Another "anti" lobby argues the potential effects of electromagnetic interference: there is no doubt you have to be careful here but in 3 million hours of Rolls-Royce Gnome engine operation in civil and military helicopters with full authority electrical control (admittedly not digital) there has not been one instance of this sort of problem - and with long airframe leads carrying relatively low level transducer signals. The Gnome in its military role has operated perfectly safely off the decks of aircraft carriers carrying extremely powerful radar and radio systems. The still sceptical reader should also note two further facts about the Gnome control, firstly it draws power from the aircraft bus only and secondly in one civil application it was not considered necessary to include reversion at all - FIGURE 2.

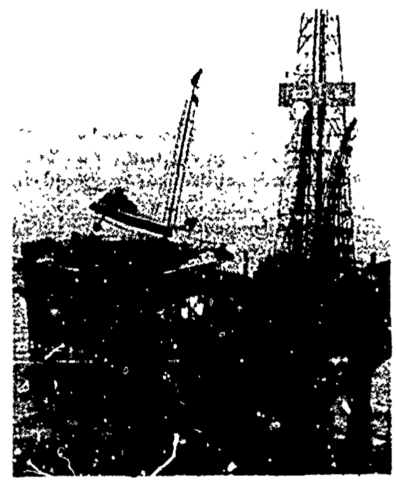

FIGURE 2 - WESTLAND WESSEX (FLY-BY-WIRE ENGINE CONTROL)

Assuming then that engine control is by electrical signals and that these signals are commanding the engine through a digital control system, a panel for a twin engined helicopter as shown diagrammatically in Figure 3 can be envisaged.

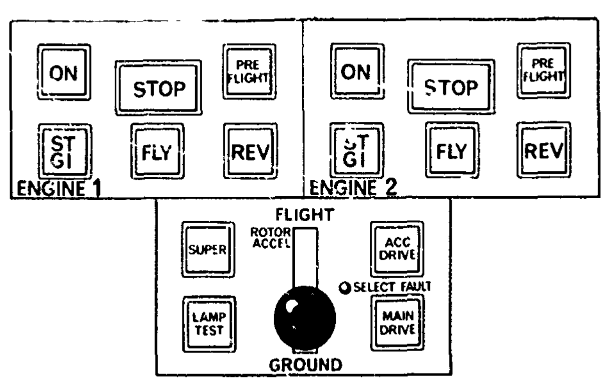

FIGURE 3 - FUTURE FORM OF CONTROL INTERFACE (TWIN ENGINED HELICOPTER)

The operation of the control panel would be as follows:-

3.2.1 Computer On-Off Select

The digital control requires a 28V power supply which must be selectable on or off for:-

(a) Ground check purposes,

(b) control below ground idle conditions, assuming an efficiently sized self powered generator is fitted,

(c) direct pilot control of the engine, assuming this is an electrical rather than a mechanical system, and

(d) as a back-up supply in the event of a self generated power failure.

3.2.2 Computer Pre-Flight Check Select

This is to allow a "go - no go" test of the control prior to engine start as an additional check to the normal in-flight self monitoring routine to check out normally dormant engine controls such as free turbine overspeed. The pre-flight check should not require any ground test equipment.

3.2.3 Engine Start/Ground Idle Select

Preferred engine start procedures may involve pre-selection of ground idling conditions and then initiation of engine start via the appropriate starter and ignition switches.

There may be some advantages in integrating the engine control with aircraft starter and ignition circuits to provide a simpler engine start procedure.

3.2.4 Flight Select

The transition from ground idle to the flight condition (i.e. governed at or near 100% speed) could, in isolation from consideration of aircraft rotor characteristics, be controlled automatically on pilot selection of the flight mode. The transition could be made to a schedule combining any of the parameters existing within the computer. An automatic transition would be applicable to the engine not associated with running up the aircraft rotor.

For the engine controlling the rotor run-up full pilot control of the rotor speed at all times is considered essential. Associated with each engine should therefore be a "fly" select control for automatic transition from ground idle to NF governing, but for the rotor run-up engine operation during the transition should be via an effective rotor speed control lever.

Where a separate accessory driving mode is required, a logic interlink between the engine controls and the selectable freewheel is proposed to replace the conventional condition lever microswitches to provide a simple safe selection procedure. The logic would require acceptable levels of speed signals before enabling freewheel actuation.

3.2.5 Reversionary Control Select

The optimum arrangement for direct pilot control of the engine is considered to be where each engine control system is designed to fail frozen and to warn the pilot that a fault condition exists. The options then open to the pilot are to leave the engine in the frozen state and rely on the power modulation available from the "good" engine for rotor speed control, to shut the failed engine down or to reset the power level of the frozen engine. Such a reset of the engine condition may be done most conveniently through a beeper switch arrangement, preferably on the collective pitch lever.

3.2.6 Shut Down Select

It must be possible for the pilot to select shut down from any operating condition though normally shut down would only be initiated from ground idle. Two separate means of shutting off the engine fuel flow should be provided in the engine fuel delivery lines for fire zone precautions.

3.2.7 Super Contingency Select

A "super contingency select" facility could be required in some cases, the intention being to allow the pilot to raise the normal contingency limits restricting engine power to higher levels for emergency use in the aircraft. A single manual selection of super contingency for all engines is assumed; it is worth noting that the initiation of the condition could be automatic, using perhaps an aircraft low rotor speed signal.

3.3 Monitoring Interface

Provided that the power plant is perfectly healthy, that it is being operated within its cleared limits and is not within a time restricted domain, the pilot does not need to know any information on engine conditions at all. At other times, the pilot is a very inefficient engine monitor, particularly under failure conditions where the odds are he is not looking at the relevant instrument(s) at the instant of the fault developing and relies on training and instinct to do the right thing. It is more likely that he will detect faults by physically sensing a change in his environment or by his attention having been attracted by warning lights etc. A recent incident has even demonstrated that given an adequate power margin and a sufficiently responsive good engine, he may not even notice such a major event as a complete engine flame out. Perhaps as a monitor of gradual change the pilot is more effective, but unless the situation is relatively straightforward (such as slowly falling oil pressure) the likelihood is that his decisions as to actions to take may not be arrived at easily - which implies a high diagnostic workload.

It has been mentioned already that the digital control can aid the pilot by carrying out some limited monitoring functions since it uses similar engine information to that displayed to the pilot. This is the point where control functions and functions previously restricted to "engine health monitoring" systems begin to be seen as overlapping. The form of the interface here is less contentious than that for the control - surely simple lights are acceptable? It is envisaged that fault conditions not requiring immediate pilot action would be indicated by an amber warning with further information available through an automatic display facility. The more serious faults would be signalled by a red warning on a central warning panel, with unambiguous indication of what the fault was.

The extent to which additional hardware beyond that needed for the control task is required for the monitoring depends on the power of the basic computer, the parameters used for control and the con-

figuration of the interface. If the task is accepted from the outset then the system can be designed to be compatible with the following monitoring without significant penalty:-

3.3.1 Control Monitoring

As part of a normal self checking routine the computer would essentially monitor all the control system equipment and should detect system faults (e.g. loss of a control signal or a faulty drive motor) as well as faults within itself. Not all of these faults will necessitate losing the whole system, for example, loss of a thermocouple used for a temperature limiting function need not affect the normal operation of the control.

3.3.2 Limit Exceedence

Engine ratings are determined by speed, temperature, torque (power) etc., levels beyond which engine operation is time restricted for lifing and certification reasons. The observance of ratings below maximum contingency is generally a pilot function and can involve a significant workload since under different ambient conditions different parameters may be the rating limiting feature. For example an engine which may be temperature limited "hot and high" may be speed limited at sea level ISA and may be torque limited under cold conditions. For this reason, and the fact that time may be very important and therefore high powers may be demanded to accomplish the mission quickly irrespective of engine or even airframe limitations, strict observance of limits may be rather neglected. No monitoring system can prevent purposeful misuse of course, but unintentional exceedence of limits can be reduced by improving the monitoring. The exceedence of rating conditions can simply be determined by the control computer by a suitable programme addition and the information relayed to the pilot in an unambiguous manner by annunciator lights, with usage of the engine being appropriately recorded.

Other engine limits such as vibration levels, oil pressures and oil temperatures can also be monitored by the computer and an indication given of limit exceedence. These parameters would require an extension of the computer hardware and, in the case of vibration monitoring, probably external transducer processing.

3.3.3 Engine Failure

Although the prime requirement here is to detect run down situations, the control cannot really be relied on for this since many of these faults may be caused by the control itself. It is possible however, to provide limited failure warning indication via the control computer by detecting such fault conditions as:-

(a) Excessive temperature for a given speed

(b) low engine power at a given temperature

(c) mismatch between spool speeds on a multi-shaft engine

(d) unusual response during transient conditions, e.g. inconsistent rates of change of speed, temperature and torque with fuel flow change.

3.3.4 Engine Usage

As a background task for the control computer, a monitor of critical engine usage (low cycle fatigue, high cycle fatigue and creep life) can be provided with data storage for subsequent readout. The definition of how these parameters are derived is beyond the scope of this paper, but apart from being of interest to engine stressmen, engine usage monitoring can pay dividends in cost of ownership terms. Ultimately engines may be released without lives as such - overhauls being undertaken as and when necessary as judged by the usage of the fatigue cycles of critical components. Whereas a reasonable basis exists for such life assessment on fixed wing scheduled airline services, using the operational pattern of the aircraft, helicopters have no similarly predictable characteristics and bearing in mind the virtual impossibility of pilot evaluation of the fatigue cycles then an automatic monitoring system here would certainly be worthwhile.

3.4 Future Form of Monitoring Interface

The pushbutton control interface described in para. 3.2 and shown on Figure 3 can be extended to include the monitoring performed by the basic control as shown on Figure 4. The annunciation of control faults is via a red warning of "freeze" on the warning panel (or of "fail" if a rundown situation exists) together with an amber on the control panel for degraded control faults. Limit exceedence monitoring is indicated by amber rating lights on the control panel: other parameters such as vibration exceedence would require an extension to the indicating system. The limited engine failure detection capability of the control would also signal the pilot through the red "fail" on the warning panel.

To obtain engine usage information from the control would require either ground based test equipment or some form of built-in interrogation arrangement. This latter represents a significant addition to the monitoring system which really becomes attractive only when its capabilities are utilised for more than usage information readout.

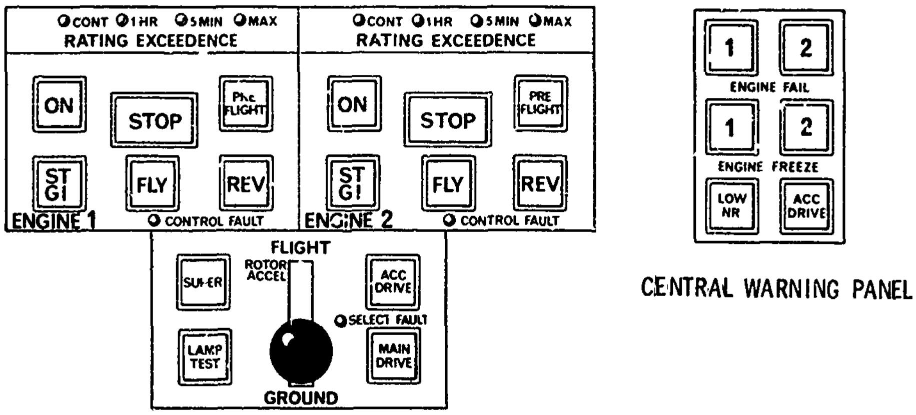

FIGURE 4 - CONTROL + LIMITED MONITORING INTERFACE (TWIN ENGINED HELICOPTER)

3.5 Extended Capability Control/Monitoring Interface

Figure 5 shows a functional form of interface not only allowing readout of monitoring data but also entry of data for both control and monitoring purposes. It should be emphasised that Figure 5 is diagrammatic only and that the actual form of the console would need to be designed to be compatible with the overall cockpit. A simpler arrangement restricting the number of pushbuttons on the facia could well be feasible, as could more advanced display systems such as cathode ray tubes. These latter would allow the simultaneous display of several different parameters in digital, analogue or even graphical form, the actual display depending on the monitoring function.

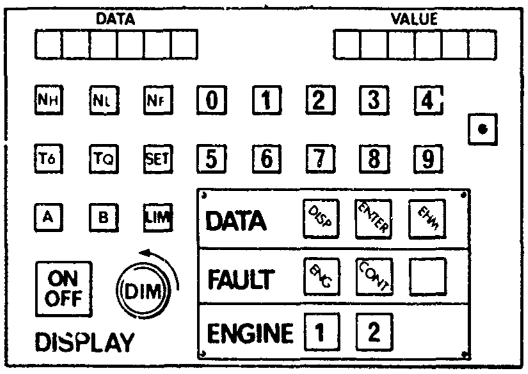

FIGURE 5 - ADDITIONAL CONTROL/MONITORING INTERFACE

The readout capability can make available on interrogation recorded usage data and also diagnostic information following the detection by the control computer of fault conditions. In addition pilot cues for system checkout could be provided, as could an accurate readout of the value of a number of selected parameters (speeds etc.) if required.

Although the use of digital techniques overcomes to a large extent the necessity for external adjustments of offset, datum drift etc., there may still be the necessity to set up the control to match specific engine or aircraft characteristics. The accessibility required of these adjustments and the form they should take may be the subject of considerable debate, but it is considered that the data recovery facility would communicate with the engine control computer via a data highway and therefore the addition of limited authority adjustments to the control may be implemented using the same highway and a data entry panel.

The general configuration of the interface can now be seen as capable of allowing detailed information to be output from a more comprehensive system dedicated to monitoring the overall engine health and performing some general aircraft management functions. Such a total aircraft health monitoring system can have many important benefits both to the pilot, the ground crew, and last but by no means least, the aircraft operator.

4. TOTAL AIRCRAFT HEALTH MONITORING SYSTEM

Though possibly only part of an even more comprehensive aircraft system, the scope of this paper only allows consideration of essentially the engine - related features of an aircraft health monitoring arrangement. The objectives here can be stated as:-

- Reduction of operating costs by providing the ground crew with appropriate data to take timely maintenance action, avoiding unnecessary work.

- Improvement of engine operating lives by accurately monitoring cumulative damage to critical components.

- Reduction in aircraft downtime by assisting in the diagnosis of engine and control malfunctions, including those caused by engine mechanical or aerodynamic deterioration.

- Reduction of pilot workload in flight by automatic monitoring of the engine and its control.

- Enhancement of the mission capabilities of the aircraft by providing pilot data relating to aircraft/engine performance on a "need to know" basis.

Not all operators would require or at least would be prepared to pay for such comprehensive capabilities and therefore to achieve the various levels of monitoring appropriate to each customer a modular system is desirable. We have seen that when engines are fitted with digital control some levels of monitoring can be incorporated within the basic control unit. As the complexity of health monitoring is increased, a point will be reached where it is more beneficial to acquire the data and output it for processing separately. The detail configuration of the total system must be a compromise between engineering and commercial pressures, and this is where the advantages of the integrated control and monitoring approach become most apparent since completely separate control and monitoring systems implies some duplication of both function and hardware. A certain amount of this may be inevitable to achieve the right levels of integrity but there are areas (such as the cockpit interface) where the two systems naturally come together and where integration can be more cost effective.

The total health monitoring system is therefore envisaged as the basic digital control computers performing limited monitoring tasks as described and communicating information to the pilot via the monitoring interface, together with microprocessor based data acquisition units providing information to a separate health monitoring central processing unit (CPU) which also communicates with the pilot through the interface. Figure 6 shows diagrammatically the system configuration: the control systems may be considered as operating in parallel with the data acquisition units and providing additional data to them.

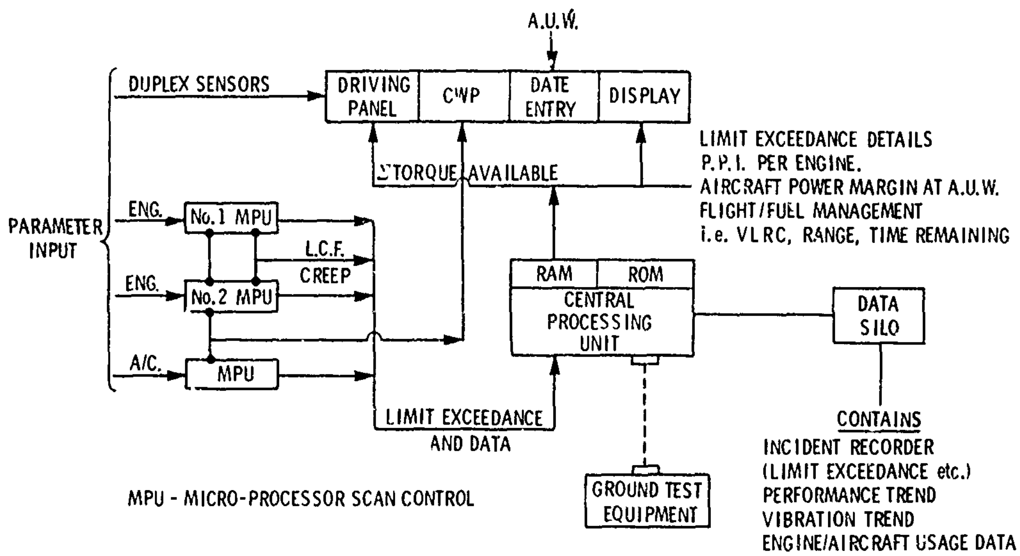

FIGURE 6 - INTEGRATED TOTAL HEALTH MONITORING SYSTEM

With urgent tasks such as limit exceedence being undertaken by the digital control, the health monitoring dedicated CPU can even out its logic and computation workload, thus allowing a modest size of unit which can be maintained at a high utilisation level. The CPU would be connected to both engine and aircraft data sources, the monitoring interface and a data silo using suitable data highways with the necessary isolation for integrity.

Basic integrity of the system can be further assured using CPU self checking procedures similar to those used for control, with a limited amount of duplicated processing for critical parameters carried out within the digital control. This ensures retention of vital data in the event of a system fault and also allows the next logical stage in the evolution of the total health monitoring concept to be considered, namely the removal of current pilot's monitoring instrumentation altogether and the substitution of fully automatic monitoring together with a display on demand of "essential" data. The operation of the total health monitoring system against the objectives stated earlier would be as follows.

4.1 Maintenance Data for Ground Crew

Information concerning the engine behaviour since the last maintenance activity (general deterioration and health, life usage, oil or fuel system maintenance etc.) can be recovered either from alterable non-volatile read only memory within the system, using the cockpit data display for routine maintenance, or from the data silo using ground based equipment in the event of a major problem.

4.2 Engine Usage

Low cycle fatigue and, where relevant, high cycle fatigue and creep life would be recorded and the relevant information made available for scheduling of aircraft maintenance or operational activities. Where on-going operation of the engine depends on the continuing accuracy of this data (i.e. the engine is released on a usage basis rather than with a defined life in hours) then separate records may be kept in the control computer and in the health monitoring CPU.

4.3 Engine Defect Diagnosis

Assuming no major engine malfunctions occur, any deterioration of performance or increase in vibration will be slow. It is therefore necessary to take sample trend data during each flight which would be passed to the data silo. This will allow the ground station to look at trends over a long period and ascertain when irregularities are occurring. On-board processing of the information as a post-flight task would be possible though incurring a hardware penalty. The subsequent display of meaningful trend data from the processing would probably only be possible using a cathode ray tube display as a pilot/ground crew interface.

Careful monitoring of trend patterns can often highlight a potential defect in the early stages, thus aiding maintenance forward programming. For major faults, it is proposed that both the engine and the aircraft data acquisition units continually pass data to a limited store in the data silo. This would contain the last few seconds or minutes of the flight prior to the fault occurring as an Incident Recorder.

Mechanical condition of the engine would be monitored using separate tracking filter units to assess each engine rotor out of balance. A vibration exceedence warning can be provided to the pilot, with further information available on demand from the pilot or ground crew.

Aerodynamic deterioration of the engine may be considered a "fault" situation only when it prevents the aircraft performing its mission. It could be argued that what is really needed here is power margin measurement, assessing for the particular aircraft conditions how the predicted capabilities of the specific engines compare with the aircraft power demands under both normal and engine failure conditions. When a negative power margin exists it would be necessary to indicate a fault, with further diagnostic data being then available through the stored trend information or via the Incident Recorder. Power margin measurement is more fully discussed in a later paragraph, together with its use as a flying instrument rather than a fault indicator.

4.4 In-Flight Monitoring

The replacement of the pilot function of monitoring such parameters as oil pressure and temperature by a simple automatic routine within the total health monitoring system should now be seen as a relatively straight-forward step, even if certification requirements still dictate an additional separate low oil pressure warning system. Control monitoring, limit exceedence, limited engine failure and engine usage monitoring have also all been discussed previously: with a separate health monitoring CPU and suitable transducer fit the system configuration should allow 100% engine health monitoring (including full control and engine failure detection), with the capability of surviving a single fault whilst retaining essential monitoring services. It is therefore argued that the provision of cockpit instruments is superfluous, their function being undertaken totally automatically. Again, the cathode ray tube form of interface would allow a flexible display format with diagnostic data on engine conditions visible immediately following detection of a fault or on demand by the pilot. Warning lights as previcusly described could provide independent fault/limit data in the event of the cathode ray tube itself failing.

4.5 Enhancement of Aircraft Capabilities

The foregoing description of the general technical capabilities of a total health monitoring system could be summed up by saying that, apart from adding one or two functions, the system can do what is currently done but very much better and with a much reduced pilot workload. Under some circumstances perhaps single pilot operation could become possible where before two were necessary, but in terms of an enhancement of capabilities this may not be seen as an overwhelming advantage. To an extent it would seem to be the aircraft manufacturer's prerogative to use the system capabilities to extend market appeal, but the following are given as examples of what is possible.

4.5.1 Fuel Management

Whilst not strictly a health monitoring function more efficient aircraft fuel management can be obtained without unrealistic pilot workload by monitoring fuel states, aircraft speeds and range. It is assumed that a NAV-AIDS system can provide distance to base and vectored wind speed data, and that Flight Manual standard data such as maximum and optimum sustained speed for a weight and aircraft specific range are stored in the program. From this data and engine fuel flows, Instantaneous Specific Range can be calculated. A final specific range can be calculated based on an all up weight (AUW) with only reserve fuel. The average of these figures versus fuel content enables a calculation of range: as this figure approaches distance to base, the pilot can be advised that he has only X minutes before a return to base is necessary. This figure would also be available on demand at any point in the sortie together with the optimum cruise speed.

4.5.2 Flight Instruments

It is claimed that there are two really essential aircraft flying instruments associated with the engine, namely the power turbine/rotor speed indicator and the torquemeter - although other engine instruments are currently provided as well (see para. 3.1). The case for a traditional rotor speed

gauge is probably irrefutable unless it is accepted that the information need only be presented on a "need to know" basis, i.e. if the rotor or free turbine departs from its nominal value or range by more than, say, 5%. It is doubtful if this "no news is good news" arrangement would really find ready acceptance and therefore in questioning the form of the essential instrumentation we will confine ourselves to the torquemeter only.

In a preceding paragraph reference to the use of an aerodynamic condition monitor as a fault diagnostic aid was made. In the context of an updated torquemeter display the monitor program resident in the health monitor CPU would contain a program assessing the potential power currently available from the engines and a program calculating the power required to fly the aircraft at the AUW and outside air temperature of the day. The former program would search for suitable steady state performance data and produce a matrix of power versus other parameters needed to define the aerodynamic state of the engine. This matrix will be continually compared with an aerodynamic model of the engine to perform data verifications. Any genuine change in the engine state will show a proportional effect on a number of parameters: if only one parameter is shown to be excessively outside this pattern, a fault warning will be generated. Once validated, this performance matrix will be used to update a data file periodically, say every 2 minutes. The data file may be used to compute the sum of potential power currently available from both engines or from the "worst" one. These figures can be directly compared on a revised torquemeter with the power requirement for the aircraft calculated using Flight Manual data or data derived from other on-board computation. The AUW figure would be input into the system prior to take off and updated during the flight from data produced by the fuel management program.

It should be noted that a less accurate version of this power margin indicator may be feasible with the basic control computer only, which would be used to predict the engine maximum power capability approximately. The torque indicator then uses the combined actual output torques from the engines to provide an actual total torque indication on one needle. Where an individual engine torque exceeds an aircraft limitation for the relevant number of engines operating, a warning of this may be given in the form of an indicator light. The torque indicator also includes a second needle which denotes the predicted maximum output torque capability of one or both engines. Thus in a high power condition or where the loss of an engine could hazard the aircraft, the pilot will be able to assess from a single indicator not only the total available torque margin but also the margin in an engine-out situation.

5. DISCUSSION

This paper has not set out to describe any fundamentally new principles of control or EHM. What has been attempted is to define those features of control and monitoring which can be seen to have a close relationship, particularly where both aspects employ digital technology. By doing this, it has been argued that control and EHM can logically be integrated. This in turn implies that the total system capability and cost effectiveness is improved if it is recognised from the start that such an integration is possible, in that the control and EHM components of the system can be designed to be complementary to each other with duplication only where necessary for integrity. The approach allows the development of a modular EHM system, with basic functions available with the digital control by relatively minor extensions to its capabilities. The paper suggests that the advent of digital control should transform the interface between the pilot and his power plants: Figure 7 summarises this new interface.

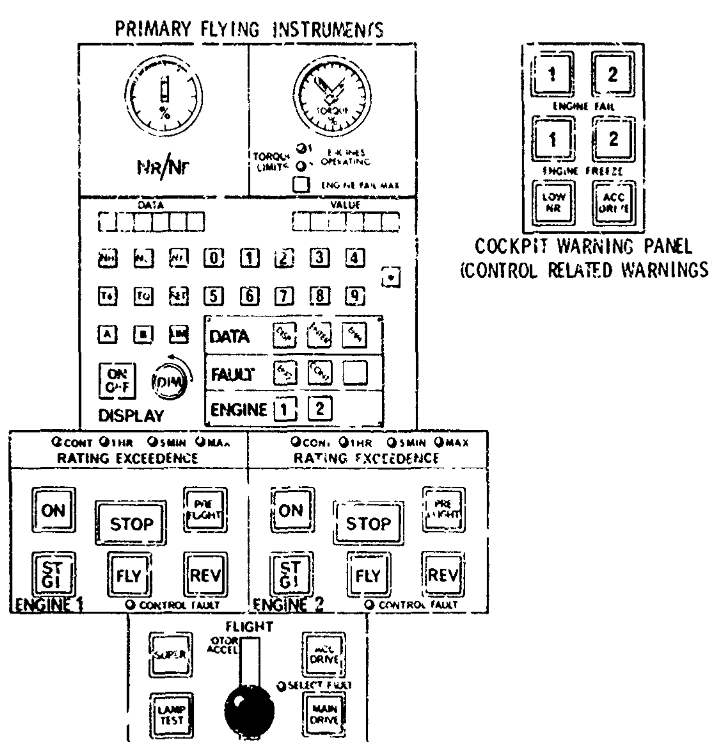

FIGURE 7 - MAN/MACHINE INTERFACE SUMMARY

Certain features of the interface suggested may be considered as controversial, such as the fly-by-wire control arrangement. The intention is to show what is possible if a sufficient determination exists to exploit the capabilities of digital systems. The trend in sophisticated military aircraft is certainly towards total fly-by-wire with the power plant seen as a sub-system addressed from a centralised digital data highway. It is suggested that this approach will eventually spread to helicopters, to reduce the pilot's workload in flight and to make most efficient overall use of the aircraft. In any event, why should the man/machine interface not be different? Perhaps mechanical levers do have a nice solid "feel" to them, but at some point the motion of metal rods must be translated into the motion of electrons and why not at source?

Although there are references to the difficulties of pilots in performing many monitoring tasks, it is recognised that helicopters have been flying very successfully for many years and therefore they undeniably have acquired adequate proficiency at it. However, piloting a helicopter is only a means to an end and there is little virtue in making the job more difficult than it need be. This is really why it is suggested that the total man/machine interface should be reconfigured, to allow a better monitoring job to be carried out automatically. Digital technology allows this to be done, and the resulting system capability is vastly superior in total aircraft health monitoring to the present "eyeball" arrangement.

Inherent in much of the foregoing is an acceptance by certification authorities of the approach taken. This paper is by no means a detailed system definition and much design work would need to be done to configure the system such that all operational and failure criteria are satisfied. It is believed that it could be easier to satisfy civil agencies on the system design than some military procurement authorities which specify how a job shall be done rather than what end result is required.

The technology to achieve the integrated system proposed basically exists. Rolls-Royce are currently involved in the design and development of digital controls for helicopter engines which could form part of such a system. Parallel EHM programmes are also in progress within Rolls-Royce aimed at full understanding of the technology, developing the software necessary to derive meaningful EHM data from helicopter engines in flight and also developing some of the necessary hardware. Significant experience has been gained in on-board digital data acquisition and with subsequent processing of data to produce engine usage and condition read-out.

The question arises as to whether any but the most complex helicopters could be fitted with such an integrated system from the cost viewpoint alone. The answer probably depends on the aircraft manufacturer's attitudes towards first cost and life cycle cost issues. Certainly the first cost is significantly higher and if this is seen as the overriding consideration then the answer is self evident although there would be some associated reduction in the aircraft costs due to installation and instrumentation savings. If, however, the cost of ownership is seen as more important then such a system must have major advantages. It is, however, difficult to quantify these until the detail design of the system has been completed and costed and the benefits defined in terms of maintenance reduction and aircraft utilisation improvements. Some of the benefits are less tangible, for example a lower pilot workload which could lead to improved flight safety is not likely to have any attributed cost savings.

Another major difficulty in achieving further progress towards a system having the capabilities described in this paper is that it requires a number of different design and procurement areas of the aircraft to be embraced. Agreement must be reached between all interested parties as to overall requirements and system configuration: it is hoped that this paper will provide the basis for further discussions within both the engine and the aircraft industries.

REFERENCE 1 "Helicopter Engine Control - The past 20 years and the next" by E.A. Simonis and M P Perks
(Paper presented at 44th AGARD Propulsion and Energetics Panel meeting on Power Plant Controls for Aero Gas Turbines held at Ustaoset, Norway in September 1974).

ACKNOWLEDGEMENTS

Whilst thanking Rolls-Royce Aero Division and the Ministry of Defence (Procurement Executive) for permission to publish this Paper, the authors wish it to be known that the views expressed herein are their own and do not necessarily represent Company or Official policy.

DISCUSSION

R.Smyth, Ge

Pilot workload. This is a comment to the speaker's remarks on reduction in workload in the cockpit.

The application of microprocessors for improving engine control must also include the external control loop of the installed engines (i.e. the control loop with the pilot monitoring engine condition). Present workload of the pilot is quite high. This can be seen by the evidence of the engine operating hand books, which are getting thicker instead of becoming thinner. Here is an area where efficient use of the microprocessor must be seen in the subject of engine control.

Author's Reply

This is one of the important points of the paper. We have heard a lot about how digital control offers the control engineer the capability of advanced control laws etc. We must not forget however that there is a man somewhere in the aircraft and we ought to address ourselves to the task of making life easier for him. Digital technology allows this to be done and the paper suggests a way of taking advantage of the technology from the pilot's and operator's viewpoints as well.

R.D.Matulka, US

What is the state of development of an integrated system such as the one you describe

Author's Reply

The control features of the system have essentially been demonstrated, including the push button engine control aspects. Both the software and hardware aspects of many of the health monitoring features are under development in a flying test bed, with off-line monitoring via data acquisition units an already developed concept.

The totally integrated arrangement described is however at this time conceptual only.

ROUND TABLE DISCUSSION

E.E.Covert: What we propose to do in the remaining time until 4 o'clock, I have asked members of the Panel

Dr Dunham	NGTE	UK
W.Kaemmer	VDO	Germany
J.Collin	SNECMA	France
Dr Bentz	Air Force	USA

to give us about a 5 minutes presentation to define what they believe the principle issues are in the area of modern control technology, and whether the evolution is in the correct direction. Finally, since all of us have heard so much about modern control technology for the past 10 years and we who are here believe firmly in it, I asked them why in their opinion modern control systems are not being installed on aircraft, helicopters and so forth.

Without further delay let us go from my left to the right and, I will be rude John, but at the end of 5 minutes I will interrupt you because time is at a premium.

J.Dunham: I don't represent any other than my own view here, I am not in any way representing the UK consensus view on what we should be doing about aero engine controls. For one thing, there are lots of other people from the UK here who can well represent themselves; and for another thing there is no such thing as a consensus of views between a group of control system people as to what we should be doing and how we should be doing it. I think that is one good reason for having a PEP meeting on the subject. If there were nothing to disagree about, there would be nothing to talk about perhaps. So I will concentrate on the disagreements, because obviously there are many aspects of control system development that we all agree on. But there are a number of significant problems that haven't yet been sorted out by experience into an agreed answer.

One of the things that is still a matter of debate is the level and type of redundancy which is necessary for any of the systems, that we have been talking about, because there is a conflict with reliability I think this is best expressed by the no-doubt-apocryphal tale of the famous French aviator Blériot when he was about to cross the Channel for the first time in his aircraft in 1909. Somebody said "You have only a single-engined aircraft. Why don't you have two engines; it would be a bit safer?" And he said, "Two of the wretched things? I have enough trouble keeping one of them going!" Well, that is really, in a nutshell, the problem that we face in deciding redundancy levels. There are supervisory systems, there are manual reversion systems, there are single lane systems, there are electronic reversion systems. This is one of the problems that remains a subject of controversy between different people.

The second question that remains to be resolved is the matter of central or distributed control functions. There are people who say that if you have a modular system then it can be safer and it can be demonstrated to be safer to our certificating authorities. To some extent that is not just modular programming but hardware modules as well, and this militates against any sort of central system. But we have also seen some papers this week suggesting that there should be grand central systems controlling a large number of functions. This again remains to be resolved, I think by experience.

A third question is related and amounts to the question that I asked this morning about the division of functions between the autopilot and the engine controller. Which part of the system is responsible for what, in an aircraft which has a large number of flight control systems and other electronic devices on board?

The fourth question which struck me as one which still remains to be resolved is the question as where to put the controller box, engine mounting or airframe mounting. It is clear that any one box is going to last longer and be lot cheaper if it is mounted in the airframe.

On the other hand, if there are a lot of sensors or any other connections to the engine, then studies have demonstrated that it is better to mount the electronics on the engine and accept the extra weight and cost involved in making it withstand the environment.

Another problem that remains to be resolved is the use of high level languages or otherwise. Here again it is a problem of visibility and a problem perhaps of compilers. At the moment there is no great problem, because there are no adequately proven compilers for the microprocessors we use. But there will be in the coming years a problem in the use of high level languages or otherwise in engine control.

There are some future problems that we must also consider. One of them is the question of multiple variables, because there is a tendency to have engines with more variables The question has already been asked, and not received a satisfactory answer, as to whether the use of modern multi-variable control theory will or will not give us a real advantage

Personally, my feelings about the meeting was that we are still in that state of technology where we inevitably had a great number of qualitative papers, and not as many quantitative results as perhaps I would have hoped. Thank you

W.Kaemmer: I have a problem, I can't be as good as you were and you have already been talking about many of the subjects I found during the session and so let me summarize and possibly even shorten. I think that whilst we heard quite a variety of brochures to my understanding, and I have to emphasise it's my own personal understanding, with all the possibilities given by the modern electronics we still have to solve the problem of the sensor side of it And I think it's a challenge of the next years, we will certainly overcome the problems described in the papers but we certainly will have to work hard to overcome the problems of the sensors And to my understanding it's the vital question. The second one.

you already have mentioned it, it is certainly to be decided, if we go to modular systems or modular in the sense of divided authorities or if we go to central systems. And one of my colleagues of VFW earlier has possibly asked the most vital question. In my understanding it is the question of the man-machine relationship. We have been looking into a cockpit of a convetional helicopter and we all know what is the task of the pilot during rather hard manoeuvres and I think the only profit we can give to those hard working guys, is to give them the tools which are already available as far as those papers are concerned we have been looking at, that they can achieve their tasks easier and by easing their tasks make flying even safer than it is today. I think this is the summarizing I can do from this and the wishes I have in the direction of this panel.

C.E.Bentz: By way of introduction, I come from the Air Force Aero Propulsion Laboratory. It is not immediately obvious to everyone that we in the propulsion community are in a change from basic hydromechanical to sophisticated electronic computation for our engine fuel controllers. This is a rather rapid change when you consider that 10 years ago we depended almost entirely on hydromechanical computation in all our fuel control systems. Today we have talked about having electronic controls on turbine engines when, in fact, many electronic controls are currently in operational service on an Air Force high-performance engine and we are now just beginning to learn important information from its usage and performance in the field. The most significant factor that influenced the selection of an electronic control for the engine was the envelope in which the airplane was to fly. And I can't help but detect from the discussions today that we, as a control community and possibly the engine community, are frustrated if not discouraged because of the limited opportunities for application of electronic controllers in current and future military and commercial systems. I must say that it takes approximately 15 years of research, engineering and acquisition development before an engine enters operational service so have patience. On the other hand, the airframe from initial design to first flight may take five years. So we must dedicate ourselves to continue our research and development activity to acquire sufficient background data to meet the reliability and cost goals of future engine applications. And along these lines, we must look for methodologies in which we can ensure the design, development and qualification of the most highly reliable system in terms of the engine-mounted hardware or off-engine mounted hardware that can be attained for that particular time period in technology. Let me explain what is meant by this statement. If we are influenced by the design requirements of the airframe industry, then two or three computers would be assigned to control each engine to achieve overall system reliability goals. From a hardware viewpoint, this may not appear to be cost effective in that the cost of the engine control system increases two- or three-fold. In addition, a software management problem may result during the service life of the engine if the engine manufacturer does not maintain total responsibility for the on-engine or off-engine mounted electronic control hardware, especially in the area of fault accommodation modes for full-authority electronic controllers. So in the next few years, I see a great need in obtaining research and development experience on engines to design and develop control systems that will accommodate faults within the software as well as within the hardware to meet the future need of having control system reliability which is as good as or better than the hydromechanical control systems which the electronic systems will replace.

One of the main advantages of the all-digital electronic control system is the ability to integrate engine components to higher levels of performance through more precise control. Hence, better fuel economy and better stability margin can be achieved both in supersonic as well as in subsonic flight. Several years ago, we conducted some research flight tests on a high-performance aircraft and found that a closed loop electronic fuel control could improve aircraft range by 15 percent during augmented operation. Using the electronic control to implement the bill-of-material control design, we could increase the altitude at which the engine could relight the augmentor by as much as 5,000 ft. Another important feature is that we could operate and relight the engine at lower Mach number, higher altitude conditions because the electronic system would automatically take over and restart the engine on spool down. So there are many advantages that can be achieved with a digital control so we must have patience and perseverance during these trying times of limited research budgets and fewer engine programs when there is not enough money to support or sustain the important work that must be accomplished.

J.Collin. La plupart des points importants on éte traités par mes collegues, je voudrais quand même ajouter que quels que soient les progres de la technologie, l'électronique tombera toujours en panne, qu'il conviendra de definir méthodiquement et systematiquement des architectures qui tiendront compte de ce facteur et dans ces conditions là, en acceptant les contraintes resultant de l'existence même de ces pannes, on pourra obtenir au niveau de systèmes propulsifs des niveaux de performance, des niveaux de succes de mission, des niveaux de sécurité de mission extrêmement éleves. La plupart des points on ete traites, je vais vous poser des questions. J'aurais aime voir abordé pendant ces sessions le probleme de la documentation des logitielles, comment écrire une documentation logitielle accessible à l'utilisateur. Je ne repondrai pas a ces question, je les pose. Un deuxième élément concerne la standardization des logitielles, lorsqu'un utilisateur doit disposer d'un avion avec 10 types de micro-processeurs, ou 15 types de micro-processeurs ayant chacun leur logitielle, leur compilateur, etc ., comment va-t-il se sortir de ce problème? N'y a t-il pas lieu d'envisager une normalisation tant au niveau des logitielles que des materiels. J'ai note également qu'un des orateurs a parlé de circuits a tres haut niveau d'integration de circuits VLSI. Est-ce qu'on connait exactement leur comportement dans l'environnement physique du moteur. Est ce qu'on a bien conscience par example que les memoires sont sensibles aux radiations résiduelles de leur boitier d'encapsulation. Est qu'on sait tester les circuits VLSI. Est ce qu'on sait tester les compilateurs de haut niveau. Encore deux questions qui sont encore plus triviales, est ce que les familles de composants sont effectivement toutes disponibles dans la pleine gamme militaire, au moins en 55 plus 125 degrés et avec des critères de deverminage et dans des niveaux a haute fiabilite, alors qu'il semble que les fabricants de semi-conducteurs s'interessent plutot au marche de la machine a laver et de l'automobile qu'au marche de l'avionique qui represente une faible part de leur production. En ce qui concerne les couts, effectivement, si on compare le cout potentiel d'un regulateur electronique

au coût d'une calculatrice de poche, on risque d'avoir quelques désappointements et en particulier aujourd'hui il y a un facteur de coût extrêmement important, c'est le coût des interfaces analogiques d'entrée et des interfaces de sorties qui pourront peut-être – bien que la nature soit analogique – être résolu par la mise en place de capteurs et d'actuateurs adaptés. J'en ai terminé avec mes questions, j'espère que lors d'un prochain congrès AGARD, j'aurai une réponse à toutes ces questions. Merci.

E.E.Covert: Thank you. I hope you all will not be too disappointed if you don't get all those answers. I think I would like to make one or two comments I will restrict myself if I may to some of the experience with the space shuttle which was not illustrated in the presentation yesterday morning. I think that there are features and consquences of that automatic control system that are not widely appreciated. One of which is that to develop a 50 000 seconds life on a large rocket with only 15 development engines is something which is unheard of. The experience with the development of the Apollo-Programme at the same point would require somewhere, if my memory is correct, in the neighbourhood of about 45 or 50 builds. Money has been saved simply by having a controller that is so quick that it can detect a difficulty and shut down the engine before the failure takes place. This alone is very impressive Now it is even more impressive when you recognise that that engine is burning a thousand pounds a second of hydrogen and oxygen so there is no such a thing as a minor fire. Under those circumstances even a trivial mistake is spectacular. A second thing that the system has been able to do is to be reprogrammed to shape the motion of the valves during starting and stopping. NASA and its contractors have effectively eliminated all of the hot spikes by making sure that the system is oxygen lean at start and shut down. This change also increases the life of the engine and increases the reliability. It also illustrates the flexibility that a digital system gives you. You don't have to bend any tin in order to make a change. you just reprogramme a card.

I could go on at great length but this would get boring after a while, so I stop here and throw the discussion open to the floor. Anyone of the people on the platform is fair game, I would appreciate it if you would address your question to one of them and not afford me the opportunity to try to decide who you want to answer your question. So go ahead please.

D.M.Griffiths: None of the panel mentioned the lack of firm projects as a contributing factor in the failure of digital controls yet to achieve production status. This may be more true in Europe rather than in North America.

Would the panel agree and would a panel member from Europe care to comment? (Which excuses the Chairman!)

J.Dunham: Yes, I think many of us have been saying we will have a digital control on our next engine When is our next engine? Of course, you are perfectly right in saying that we haven't got digital control committed to an engine because the last engine we committed was now some years ago.

E.E.Covert. There is a lot of talk about a 1990's fighter, if Dr Bentz's discussion of 15 years to an engine bears any truth at all it seems to me that they better get on the stick, if I might use that expression. Do you think that is going to happen? A 1990's fighter is going to be laid down?

J.Dunham: Yes.

E.E.Covert: Is there evidence that the engine is about to be started to that?

J.Dunham: I don't know whether it will be a new engine. Obviously one does not know at this stage whether these fighters either in the US or in Europe will have existing engines or new engines. But what we are living in hope and indeed conviction about is that, whether it is an old one or a new one, it will have a digital control box on it.

I.S.D Stitt: Keyword Projects. Mr Bentz outlined the advantages that can be achieved with electronic controls. Would he care to comment on whether these advantages would be achieved by retrofitting the controls on existing engines and whether this would be cost effective

C.E.Bentz: Yes, there would be advantages in engine performance and in operational and support costs in retrofitting controls on existing engines, howev , the cost is strictly prohibitive to go back and requalify an electronic control for an in-service engine, plus the cost an . logistics of reconfiguring every engine control in a timely manner. It is barely enough money to build a new engine with an electronic control Of course, you can estimate the advantages of an electronic control system, but it is hard to prove it to anybody with service experience. There are certainly advantages in fuel savings and improved thrust performance with an electronic control system, but the cost would be prohibitive to go back and retrofit every engine with an electronic box.

G.E.Davies: We have heard many interesting papers in the last two days showing the great power and versatility of digital control systems Most of these covered work on existing engines where the original control system was replaced by a digital system We have also heard in one or two papers a suggestion that engines might be made more efficient by reducing the number of compressor stages, for example, and using digital techniques to run much closer to surge than is possible at present My question is a general one and is this Will we have the courage in the next engines to be designed to make them irrevocably dependent on the full capability of digital control systems by designing them to work much closer to all the performance and stability limits?

C.E.Bentz: Every new engine that we are looking at have components that are more highly loaded than before and are considering full-authority, digital controllers to better regulate the engine throughout its operational envelope. Because we are designing for greater performance and maintainability in future engines, we are also including diagnostic functions in the control to detect control malfunctions and monitor engine component degradations.

E.E.Covert: One quick question. You talk about electronic controls, are you talking about a system in which the loop is always closed?

C.E.Bentz: Yes.

E.E.Covert: It was not clear to me in some of the discussions that we have had in the last few days, whether an electronic system was an open loop or closed loop system, and I believe the advantages of a closed loop are so great that it would not be wise to think much longer about open loop systems.

J.Dunham: I was going to say something quite similar. We cannot utilize a reduced surge margin at the moment in controls based on fuel scheduling, because of engine deterioration and engine inlet distortion problems and so on. The only way we could really guarantee being able to run with a much reduced surge margin and design for that initially would be to have a closed loop. To have a closed loop you have to detect the incipient surge in some way. At the last AGARD controls meeting I presented a paper showing how you could have a closed loop control which will stop reheat buzz; but you can't do this with surge. With some engines it has been demonstrated long ago, but we can't guarantee to detect incipient surge on every engine in time to take action to avert it, and hence generate a closed loop. That is not a digital control problem, it's a problem of compressor technology.

J.F Evans: The reliability of high level compilers has been questioned. Does the panel think that is not similar to doubting the quality of a component produced in an automatic milling machine? Evidently in either case the resulting product is harder to test. In both cases mistakes once made can be 'designed out' for future components.

J.Collin: Il ne s'agissait pas d'opposer des pannes de composants mécaniques sur lesquelles j'ai assez peu de donnéeaux pannes de composants numériques, mais je crois que l'introduction des circuits numériques nous oblige à prendre en compte des pannes transitoires ou des pattern sensitives qui n'existent pas jusqu'à present dans les systèmes analogiques que nous utilisons.

D.J.Hawes: As environment has such an influence on reliability would it not be advantageous to the environment to be specified by the engine manufacturer to the control vendor based on expected values in a specially designed mounting rather than the "ad hoc" manipulation of MIL-Specs, and the alternative of airframe mounting with the associated management problems. I believe that in future instead of just taking MIL-Spec, and guessing at some profile, would it not be better if the engine manufacturer was to take the responsibility of providing the environment for the control system just as it is now on the gearbox for example for highly mechanical control?

E.E.Covert: If I may say so, that is a very valid suggestion I know of at least one application in the United States, where the situation was finally resolved by measuring the acceleration and the temperature and acoustic level at the equipment location and designing the equipment to live in that environment. Of course, one must design a sort of test to ensure that the environment could be duplicated in a laboratory and the equipment would satisfy those requirements In this case it was of utmost importance to be able to duplicate the engine environment in the laboratory Before the latter step was taken the equipment was not very satisfactory because even though it passed all the other SPECs it would not live happily with the engine.

R.Lo:

(1) Should the implementation of CCU technology be integrated with proper engine controllers? Will engine control bring an additional dependency upon well working computers?

(2) Is the community aware of the effort at the University of California to base engine health monitoring on acoustical analysis of the engine noise? (It has been demonstrated that this is feasible and it surely requires a lot of data processing.)

C.E.Bentz: In cases that I have observed, the controller is much faster in response than any of the dynamics of the rotating engine components The actuators, in some cases are limiting, especially those that move large loads. The control strategies and the speed of the computer need to be looked at very carefully If you implement a control design on the basis of a single-input, single-output system using classical techniques, and you handle all the cross couplings of a multi-loop engine (3 loops, 4 loops, 5 loops and so on) you soon run out of cycle time in the computer. In my opinion, classical techniques can no longer be used to design controllers for future complex engines where there is a high degree of cross coupling and maintain adequate stability margin for the engine across the flight envelope. Therefore, more advanced design techniques such as multi-variable strategies must be considered for engine control problems where there are a large number of interactions

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The Meeting was in five sessions: Development Experience, Control Implementation, Optimum Control Strategies, Digital Control Concepts, and the Round Table Discussion

The meeting was focussed on current and projected developments in control systems for aircraft powerplants. The application of digital control technology on aircraft turbine engines was especially emphasized. The meeting served as a platform for discussion and exchange between research scientists, development specialists and applicants of control systems.

Whether the meeting achieved its initial aim of furnishing a comprehensive control system technology survey will be assessed in a Technical Evaluation Report to be published as AGARD Advisory Report AR 152.

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